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D-998

MEASUREMENTS OF TOTAL EMITTANCE OF SEVERAL REFRactory
OXIDES, CERMETS, AND CERAMICS FOR TEMPERATURES
FROM 600° F TO 2,000° F

By William R. Wade and Wayne S. Slemp

Langley Research Center
Langley Air Force Base, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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SUMMARY

Experimental measurements of total emittance are presented for a variety of refractory materials that are believed to have possible use as temperature control surfaces for high supersonic and hypersonic aircraft. The following table lists the materials and the most significant results obtained:

Material	Temperature range, OF	Total emittance range
Chemically oxidized Inconel	600 to 1,600	0.91 to 0.94
Chromium oxide base paint	600 to 2,000	.78 to .94
Aluminum oxide base paint	600 to 1,800	.82 to .83
Silicon carbide ceramics	600 to 1,800	.94 to .62
Silicon nitride ceramic	600 to 1,800	.89 to .78
Chromium/aluminum oxide cermets	600 to 1,600	.76 to .94
Flame-sprayed cermets	800 to 1,800	.84 to .94

INTRODUCTION

Hypersonic and supersonic aircraft operating in the atmosphere of the earth are subjected to conditions of severe aerodynamic heating which may cause a high temperature increase of the vehicle skin. This temperature increase may exceed the structural limit of the aircraft unless it is limited by some method. One of the most suitable means of limiting this temperature rise is the utilization of radiative cooling, since this method is inherently simple, reliable, and does not add significantly to the total weight of the aircraft.

For a material to be an efficient radiator, the total hemispherical emittance must be high, since the rate of radiant heat loss is directly proportional to the total emittance. Therefore, it is apparent that

practical interest lies in the development of surfaces having high values of total emittance.

In reference 1, Worthing recommended that the term "emittance" be used instead of the term "emissivity" to denote a characteristic of a body rather than the material of which it is composed. This recommendation has gained acceptance by others in recent years (ref. 2) and is adopted in the present work to emphasize that the surfaces studied are defined basically by the method of preparation and to avoid any implications that the surface substance is of uniform composition, chemically definable, highly polished, and of essentially infinite thickness.

The clean smooth metals generally used for construction of high-speed aircraft have a low emittance and are poor radiators; therefore, if a metal of this type is to be used, a high emittance coating may be necessary. One method which may be used to obtain the desired coating is the oxidation of clean metals in air at elevated temperatures. For many metals this treatment will produce a thin adherent coating which is aerodynamically smooth and which has high values of total emittance. Although a quantity of emittance data for oxide coatings is available in technical literature, much of this information is incomplete. Factors such as the time and temperature of oxidation, the adherence of the coatings to the substrate material, and their resistance to mild abrasion and thermal cycling must be known for coatings to be used for radiative cooling of high-speed aircraft.

For these reasons, the National Aeronautics and Space Administration is currently engaged in a research program to determine the total emittance of a wide variety of possible aircraft construction materials. Previous results from this program are presented in references 3 to 5 and include data for stably oxidized metals, flame-sprayed ceramic coatings, and some refractory hard metals. The present investigation includes results obtained for chemically blackened Inconel, refractory paints, and some ceramics and cermets.

SYMBOLS

f radiant flux density, Btu/(sq ft)(sec)

T absolute temperature, °R

φ angle of observation as measured from normal, deg

Subscripts:

b black body

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0 at $\phi = 0$ (normal to surface)

u surface of unknown emittance

APPARATUS

L The methods most generally used to determine total hemispherical
1 emittance are the "filament-in-vacuum" and the "reference-black-body"
5 methods. Although both methods have certain limitations, the reference-
7 black-body method seemed especially well suited for the wide variety of
2 materials and surfaces to be encountered in this program. The apparatus
used for this investigation is fully described in reference 3; therefore,
only a brief summary is presented herein.

An overall view of the emittance measuring apparatus is shown in figure 1 with identification of the principal components. The reference black body used in this investigation was a heavily oxidized Inconel cone, 6 inches in length, with an apex angle of 8.6° . A theoretical evaluation (ref. 6) indicates that a black body of this type, when equipped with the proper aperture-limiting baffles, is superior to other types of construction.

The heat source for the black-body reference cone was a commercially available tube-type furnace commonly used for gas analysis. The radiation-sensing thermopile, used to measure the radiant flux density emanating from a heated specimen or black-body target, was a commercially available total radiation pyrometer. This detector consisted of a chromel-constantan thermopile, a cold-junction compensating resistor, and an optical system for focusing the radiant flux density on the thermopile hot junctions.

The specimen rig and associated power supply were designed for the resistance heating of metal test specimens to temperatures near their melting points. This rig holds the test samples in a vertical position, with provisions to prevent buckling of the specimen due to thermal expansion at high temperatures. A pivoted arm, for attachment of the thermopile, allows measurement of radiant flux density at angles of observation from 0° to 60° from the normal to determine any deviation from Lambert's cosine law.

The water-cooled shield-and-shutter arrangement is used as an aperture-limiting baffle and serves to prevent extraneous radiation from reaching the thermopile, so that the temperature rise of the thermopile housing is limited to a negligible amount.

Temperatures of the reference black body and the test specimens were measured by chromel-alumel thermocouples of No. 30 gage (American wire gage) spot welded to the surface of the reference cone and metallic or cermet test specimens and potted into a shallow hole for the ceramic materials. The temperature was obtained from an automatic balancing potentiometer equipped with a self-contained cold-junction compensating resistor and calibrated to measure temperature directly in °F.

The thermoelectromotive force produced by the pyrometer as a function of the incident radiant flux density was determined by a manual-balance precision potentiometer.

PROCEDURES

The procedures used to obtain the values of total hemispherical emittance are essentially the same as those used throughout this program and are described in detail in reference 3. Although originally designed to enable measurement of total hemispherical emittance of stably oxidized metals, the equipment and procedures have been successfully used for painted coatings, flame-sprayed refractories, and bulk refractory materials. Experience has shown that the most convenient procedure is to measure the radiant flux density from the black-body reference over the entire temperature range from 600° F to 2,000° F rather than to view the black body and test specimen alternately at each temperature. These values are then considered a calibration of the measuring system, and only a periodic check is required to determine any drift or change. During the course of these measurements, the system was calibrated three times - before the tests were begun, near the midpoint of the tests, and after completion of the tests.

The calibrations shown in figure 2, wherein the thermopile potential is shown plotted as a function of black-body temperature, indicate only insignificant differences between calibrations. The additional scale shown on the calibration plot is of radiant flux density relative to the black-body flux density at a temperature of 1,000° R. These relative values of flux density are used for determining values of total emittance since it is not valid to assume that the response of the apparatus is directly proportional to the actual flux density. This method of obtaining emittance values eliminates any error due to the nonlinearity of the apparatus, and the requirements on the instrumentation are greatly reduced.

In all tests, two identical specimens were used; these are designated as specimens 1 and 2 in the figures. The procedure followed for the investigation of test specimens required a preliminary check to determine the emittance stability of the material. This check was accomplished by

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holding the test specimen at some specific temperature while making periodic measurements of the radiant flux density. When the measured values of flux density no longer changed with time, the material was considered to have a stable emittance for temperatures up to the specific oxidation temperature.

A preliminary visual check on the adherence of the surface coating under conditions of increasing and decreasing temperature was conducted. This test consisted of increasing the specimen temperature from ambient temperature to the maximum oxidation temperature and then allowing the specimen to cool. One complete cycle required about 2 minutes, and the test samples were subjected to a minimum of six cycles.

A test to determine the resistance of a coating to mild abrasion was conducted by rubbing the surface with a medium-grade silicon carbide polishing paper and then visibly checking the results.

When possible, an investigation was conducted to determine whether the test material emits diffusely in accord with Lambert's cosine law. The procedure was to measure the radiant flux density from the sample at angles of observation from 0° to 60° from the normal, at temperatures from 600° F to the maximum oxidation temperature. The measured values were corrected for the increased surface area viewed, and the ratio of the radiant flux densities from the sample and the black body were calculated and plotted along with the Lambertian representation of a perfectly diffuse surface.

If this test indicates that the measured angular distribution of emittance conforms to Lambert's cosine law, within the limits described, the measured total normal emittance values would be considered a close approximation of the total hemispherical emittance. Angles of observation were limited to 60° by the practical consideration of specimen size; however, any deviation from Lambert's law at angles of observation greater than 60° causes an error in total hemispherical emittance values of only 1/4 of this percent deviation.

In some cases, the size or temperature uniformity of the specimen was not sufficient to permit observation from directions appreciably removed from the normal; in all such cases, however, the Lambertian distribution was considered to be adequately valid.

TESTS AND RESULTS

Chemically Oxidized Inconel

The technique described in reference 3 for obtaining an Inconel oxide coating with a high stable value of total emittance is not practical for all applications. For this reason it is desirable to obtain an Inconel coating which could be applied to complicated shapes after fabrication and which would possess radiation characteristics similar to those of the aforementioned coating.

One method of attaining this result is to blacken an Inconel surface with a saturated aqueous solution of sodium dichromate. When heated at 800° F, this solution reacts with the chromium constituent of Inconel to form an oxide comprised primarily of CrO, as determined by X-ray diffraction analysis. For this method the surface preparation is important only to the degree that will allow complete wetting of the surface by the salt solution. This process requires that polished surfaces be carefully degreased and preoxidized (at 800° F) before the solution is applied. The Inconel specimens are then sprayed with the salt solution, placed in a clean, dust-free furnace, and held at a temperature of 800° F for 30 minutes to allow the reaction to take place. After this treatment a thorough swabbing with cotton under distilled flowing water completes the specimen preparation.

The emittance stability of this oxide was determined by obtaining measurements of the total normal emittance as a function of time at a constant temperature of 1,600° F and also at 1,800° F. The results of this test (fig. 3) indicate no appreciable change of emittance for samples held at a temperature of 1,600° F for a period of 30 minutes. The values of total emittance vary from 0.90 to 0.94 over this temperature range. Specimens held at 1,800° F for 30 minutes, however, show a definite decrease of emittance with time which corresponds to changes in the surface coating.

Visual examination and X-ray analysis of the samples after this test showed no change in either the appearance or composition of the coating exposed to a temperature of 1,600° F. The samples held at a temperature of 1,800° F, however, did show a visible change in the oxide coating that was proven by X-ray diffraction to be a mixture of NiO and Cr₂O₃, in addition to the original CrO coating.

The effect of this change in coating composition on the emittance of the samples is further shown in figure 4, where values of total normal emittance as a function of temperature are shown for specimen 1 held

at 1,600° F and specimen 2 held at 1,800° F for 30 minutes. The close agreement between measured values of emittance before and after exposure to 1,600° F, together with the significant differences for the sample exposed to a temperature of 1,800° F, is evident.

The purpose of this method of oxidizing was to eliminate the necessity for the high-temperature oxidation of Inconel in air in order to obtain a high stable emittance. Thus, this coating fulfills its intended purpose only to a limited degree and appears to be unsuited for use at temperatures in excess of 1,600° F where stable emittance is required.

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The investigation to determine whether this chemically oxidized Inconel emits diffusely in conformance with the Lambert cosine law was conducted on specimens held at 1,600° F for a period of 30 minutes. Measurements of the radiant flux density were made at angles of observation from 0° to 60° from the normal over a temperature range from 600° F to 1,600° F. For simplicity, measured values for only 600° F and 1,600° F are shown in figure 5. The circle is the plot of Lambert's cosine law for perfectly diffuse emission. The close agreement between measured values and Lambert's cosine law indicates that this coating emits diffusely over the range of temperatures and angles considered. Therefore, the measured values of total normal emittance are close approximations of total hemispherical emittance.

Refractory Paints

Pyromark paint.- Included in the materials investigated was a refractory paint, Pyromark, manufactured by the Tempil Corporation (132 West 22nd St., New York, N.Y.). Although the exact composition of this paint is not available from the manufacturer, it probably contains finely ground chromium oxide powders which produce a flat black. The paint may also contain a small amount of graphite, plus a silicate binder and an organic vehicle. An X-ray diffraction analysis indicated only the presence of CrO. This paint is of interest because it will allow normal metal forming and fabrication procedures that may not be possible with some other types of coatings.

For the Pyromark coating, specimen preparation consisted of applying the paint in thicknesses of approximately 0.001 inch to solvent-cleaned metal strips of "as-rolled" stainless steel 321 and of polished Inconel. The coated specimens were then air-dried at room temperature for at least 24 hours before testing. A preliminary investigation to determine the adherence of this paint to a metallic substrate and the emittance stability at elevated temperatures was conducted on both the stainless steel and Inconel specimens. This investigation indicated that the Pyromark coating has a high total normal emittance that remains

essentially stable at temperatures up to 2,000° F as shown in figure 6. Visual examination of the test samples indicated no appreciable effect on the coating after exposure to temperatures as high as 2,000° F for a period of 15 minutes.

Subsequent measurements of the total normal emittance for both the Inconel and stainless-steel specimens over a temperature range from 600° F to 2,000° F are shown in figure 7. These curves indicate that slightly different values of emittance may be obtained by applying the Pyromark to different substrate materials, the values increasing from 0.81 at 600° F to 0.94 at 2,000° F for the polished Inconel and from 0.78 at 600° F to 0.90 at 2,000° F for the as-rolled stainless-steel substrate.

To determine whether the Pyromark-coated specimens emit diffusely in accordance with Lambert's cosine law, measurements were made of radiant intensities from the test specimens at angles of observation from 0° to 60° for a temperature range from 600° F to 2,000° F. The results of this investigation for 600° F and 2,000° F are shown in figure 8, where the circle corresponds to Lambert's cosine law for perfectly diffuse emission. The close agreement between the measured values and Lambert's cosine law indicates that this coating emits diffusely for the temperatures and angles considered. Therefore, the measured values of total normal emittance are close approximations of total hemispherical emittance.

Aluminum oxide paint.— For the tests in which specimens were coated with aluminum oxide paint, the coating was applied to Inconel strips stably oxidized, as described in reference 3, by common paint-spraying techniques. The paint thicknesses were approximately 0.001 inch, 0.002 inch, and 0.003 inch.

The preliminary investigation to determine the emittance stability of this coating was conducted at a constant temperature of 1,800° F. The results of this test, as shown in figure 9, indicate that the emittance attains a stable value after approximately 15 minutes at this temperature. The slight increase of emittance during the initial 15-minute period may be due to the decomposition of the organic vehicle. Examination of the test specimens after 30 minutes at 1,800° F indicated no apparent change of the coating. An increase of temperature to 2,000° F, however, tends to char the coated surface, which restricts the use of this paint to temperatures considerably lower than those originally expected.

The measurements of total normal emittance are shown in figure 10. In this figure the measured values of total emittance are plotted as a function of temperature of the Inconel substrate and show nearly constant values of emittance for the three coating thicknesses.

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The investigation to determine whether this coating emits diffusely in accordance with Lambert's cosine law was conducted on test specimens over the temperature range from 600° F to 1,800° F at angles of observation from 0° to 60°. The results for temperatures of 600° F and 1,800° F are shown in figure 11. The close agreement between the measured values and Lambert's cosine law, represented by the circle, indicates the measured values of total normal emittance are close approximations of total hemispherical emittance.

Ceramics and Cermets

The test specimens used for the investigation of ceramic and cermet coatings were 1-inch-diameter circular disks approximately 1/4 inch thick. Specimen preparation consisted of grinding and polishing the sample to obtain a smooth, flat surface; a thorough cleansing with alcohol and distilled water completed the specimen preparation. The size and shape of the specimen made the resistance heating methods used for other materials impractical in this case. Therefore, Inconel strips were used in the specimen heating rig as resistance heaters, and the sample disks were placed on these strips and heated by thermal conduction.

The temperatures of the samples were measured by chromel-alumel thermocouples No. 30 gage (American wire gage) attached to the sample surface viewed by the radiation-detecting thermopile but outside the field of view of the detector. For the ceramic specimen a small shallow hole was drilled into the specimen and a beaded chromel-alumel thermocouple No. 30 gage (American wire gage) was potted into the hole with a commercially available porcelain cement (Sauereisen No. 1). The angular distribution of emittance could not be readily determined for the 1-inch-diameter disks. However, the composition and surface finish of the specimens probably insure diffuse emission so that the measured values of total normal emittance closely approximate values of the total hemispherical emittance.

Pertinent information including the density, heat capacity, and thermal conductivity of these materials as well as values of weight change experienced by these materials when tested in a 3,800° F air jet is discussed in reference 7.

Ceramics. - The ceramics tested in this investigation were various SiC-base materials furnished by several manufacturers. They include a pure SiC (Crystolon "R") from the Norton Co., a SiC + C mixture (No. 62) from Alfred University, a SiC + C mixture (830 series) from National Crucible, and a SiC + Si mixture ("Durhy") and a pure Si_3N_4 mixture (No. 2817-C) from the Carborundum Co. The results are presented in figures 12 to 21. For the preliminary tests, which were conducted to determine the emittance stability of these materials, measurements of

the radiant flux density were obtained as a function of time at a constant temperature of 1,800° F. When the measured values ceased to change the specimens were considered to be stably oxidized for temperatures up to this oxidation temperature. The results of these tests are presented in figures 12, 14, 16, 18, and 20. These ceramics all show a decrease of emittance during the time of oxidation. The greatest decrease was experienced by the specimens composed of silicon carbide with added carbon; the smallest decrease was recorded for the silicon nitride specimens.

After emittance stability was ascertained, values of total normal emittance as a function of temperature were obtained for all test samples over the temperature range from 600° F to 1,800° F as shown in figures 13, 15, 17, 19, and 21. These silicon carbide and silicon nitride base materials all show a nearly linear decrease of emittance with increase of specimen temperature, a characteristic of many ceramic materials over this temperature range.

Values of emittance obtained for a SiC sample (Norton's Crystolon) are shown in figure 13 to vary with temperature from 0.90 at 600° F to 0.84 at 1,800° F. Emittance values of SiC + C specimens obtained from Alfred University were found to vary from 0.90 at 600° F to 0.70 at 1,800° F (fig. 15). Values of total emittance from 0.94 at 600° F to 0.75 at 1,800° F were obtained for specimens of SiC + C received from National Crucible (fig. 17). The SiC + Si samples obtained from the Carborundum Co. had measured emittances ranging from 0.94 at 600° F to 0.62 at 1,800° F (fig. 19). A Si₃N₄ sample also obtained from the Carborundum Co. had measured values of emittance ranging from 0.89 at 600° F to 0.78 at 1,800° F (fig. 21).

The scatter observed in the values of total emittance obtained for specimens of similar composition is probably due to the variability of the specimen surfaces, which have a considerable number of voids. However, the values reported herein are believed to be reproducible for other specimens of like composition, within engineering accuracy.

Cermets. - Cermets, combinations of a metal and a ceramic, are produced by specialized metallurgical techniques of pressing and sintering the powdered components. The resulting materials are metallic in nature and possess some advantages over the pure ceramic refractories. The cermets included in this investigation combine metallic chromium and aluminum oxide, constituents that normally have good high-temperature mechanical properties and resistance to oxidation. The oxidation resistance is increased in the cermet by formation of a chromium oxide film which is very adherent and highly stable while the aluminum oxide ceramic phase is naturally stable. Thus, these materials show promise as engineering materials in applications where high-temperature stress and mechanical wear occur.

The cermet materials investigated were produced by Haynes Stellite Co. from which the following designations and composition, in percent by weight, were supplied:

Components	LT-1	LT-1B	LT-2
Chromium, percent	77	60	25
Aluminum oxide, percent	23	19	15
Molybdenum, percent	--	19	--
Titanium dioxide, percent	--	2	--
Tungsten, percent	--	--	60

A preliminary investigation to determine the emittance stability of these materials was conducted at an oxidation temperature of 1,600° F. The results of this test, shown in figures 22, 24, and 26, indicate that these materials all form a surface oxide which attains a stable emittance for this temperature after exposure for 10 to 15 minutes.

Visual examination of the specimens after this preliminary investigation showed that a thin, smooth adherent oxide formed on the surface. An X-ray diffraction analysis of this coating proved it to be essentially Cr_2O_3 .

The measurements of total normal emittance for the stably oxidized specimens over a temperature range of 600° F to 1,600° F are plotted on figures 23, 25, and 27. These results show a nearly linear increase of emittance with temperature from 0.79 to 0.90 for the LT-1 cermet, from 0.79 to 0.94 for the LT-1B cermet, and from 0.76 to 0.91 for the LT-2 cermet.

Flame-sprayed cermets. - Total normal emittance measurements were also made on the Haynes cermets flame-sprayed on sandblasted, oxidized Inconel substrates. For these tests, the Inconel strips were sandblasted, etched, and oxidized as described in references 3 and 4, and the coatings were applied in thicknesses of 4, 6, 8, 10, 12, and 14 mils.

The test specimens were heated by resistance heating of the Inconel substrate and the temperatures were measured by a chromel-alumel thermocouple spot-welded to the Inconel surface.

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During the tests, the radiant flux density detected by the pyrometer originates from both the flame-sprayed cermet and the metal substrate up to a certain limiting thickness of the coating. This limiting thickness is governed by the particle size and the refractive index of the coating material as discussed in reference 8. Further, there is an unknown temperature drop through the coating for which a correction may be made by using the following procedure.

Values of total normal emittance of each test strip were obtained over a (substrate) temperature range from 800° F to 1,800° F and plotted as a function of coating thickness as shown in figures 28, 29, and 30. A plot of the data obtained for Haynes LT-1 at a temperature of 1,200° F is shown in figure 31. The curved portion of this figure, for coating thicknesses from 4 to 10 mils, indicates that the coating is below the limiting thickness and partly transparent to infrared radiation from the Inconel substrate. The linear decrease from 10 to 14 mils coating thickness indicates that the coating is effectively opaque for coatings greater than 10 mils and that the further apparent decrease of emittance is assumed to be due to temperature drop through the coating. It can be shown that a plot of emittance against thickness will be a straight line of negative slope. Therefore, extrapolation of the linear portion of the curve shown in figure 31 to zero thickness should result in reasonably accurate values of emittance for these cermet coatings at the temperature of the Inconel substrate.

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The emittance values obtained by this method for the Haynes flame-sprayed cermets are shown in figure 32 as a function of the Inconel substrate temperature. These curves show a nearly linear increase of emittance over a temperature range of 800° F to 1,800° F, values ranging from 0.84 to 0.90 for the LT-1 cermet, from 0.88 to 0.94 for the LT-1B cermet, and from 0.86 to 0.90 for the LT-2 cermet.

As was the case for the bulk ceramic and cermet materials tested, the investigation normally conducted to determine how closely the emission obeys Lambert's law could not be performed.

SUMMARY OF RESULTS

The investigation of chemically oxidized Inconel indicates that, although a high stable value of emittance may be attained by this process, exposure to temperatures in excess of 1,600° F causes a change in the surface coating due to the formation of another oxide. This change in the oxide results in a change of total emittance, limiting this coating to fairly low temperature applications where stable emittance is desired. The measured values for this coating were found to vary from 0.91 to 0.94 over a temperature range from 600° F to 1,600° F.

Results obtained for the paint coatings tested, specifically chromium oxide paint (Pyromark) and aluminum oxide paint, indicate the coatings have high stable values of total emittance. The emittance values ranged from 0.78 at 600° F to 0.90 at 2,000° F for the Pyromark coating on "as-rolled" stainless steel 321 and from 0.81 at 600° F to 0.94 at 2,000° F for this same coating on polished Inconel.

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Emittance measurements of a variety of silicon carbide and silicon nitride materials show fairly high values of total emittance, which proved to be quite stable, after oxidation in air at 1,800° F. The measured values for these materials show a decrease of emittance with increasing temperature over the temperature range considered, a characteristic of most ceramic materials. The total emittance for these stably oxidized materials varied from 0.94 at 600° F to 0.62 at 1,800° F.

The cermets investigated were primarily chromium/aluminum oxide composites. Certain modifications of these basic components result in three distinct materials which were designated by Haynes Stellite Co. as LT-1, LT-2, and LT-1B. These materials were all reported to have good thermal shock properties, resistance to oxidation and to mild abrasion, and high stable values of total emittance. The results of measurements conducted on these cermets show a nearly linear increase of emittance over a temperature range from 600° F to 1,600° F, ranging from 0.76 to 0.94 for the three materials tested.

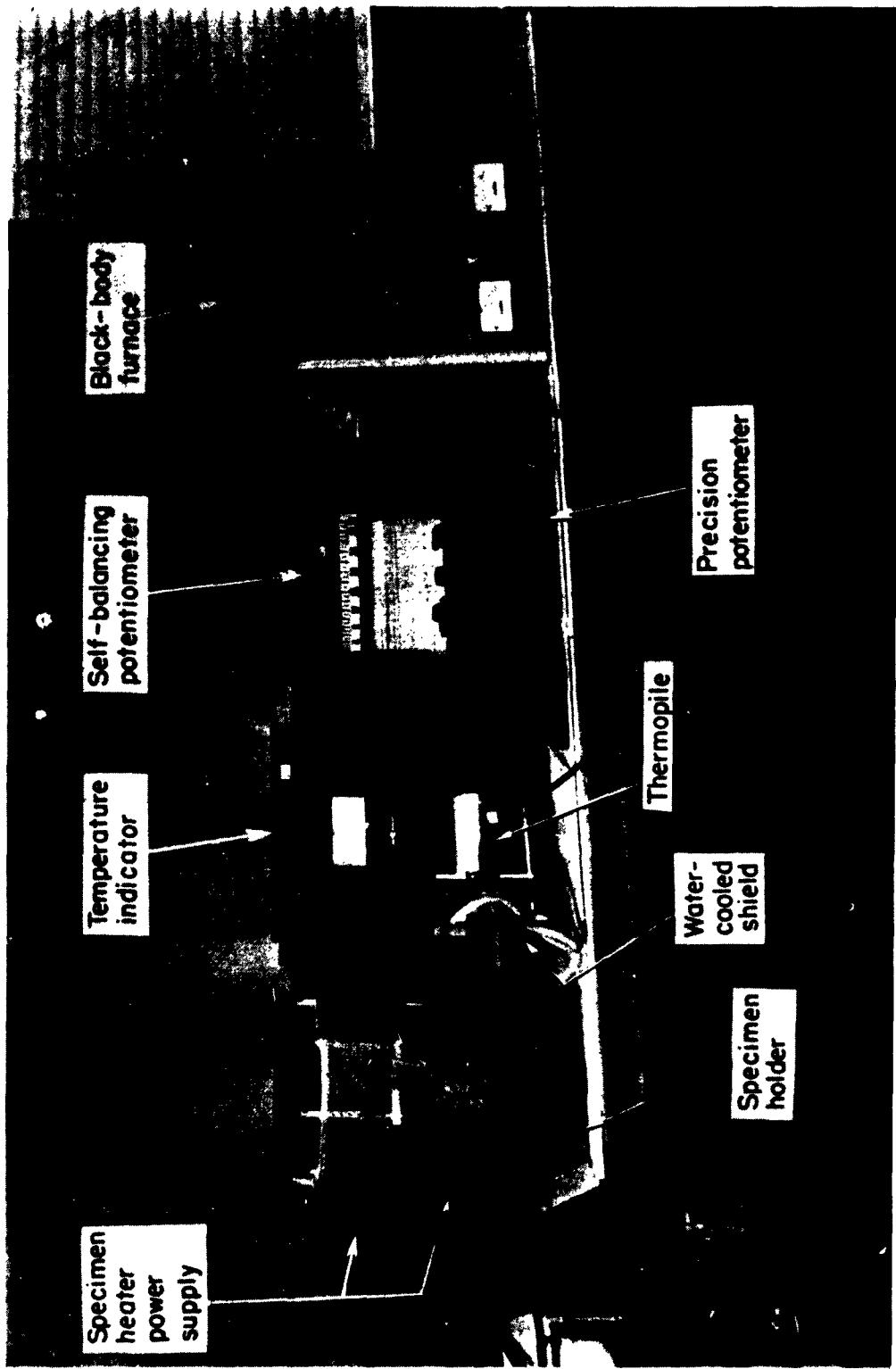
Investigation of the total emittance conducted on flame-sprayed coatings of the cermets indicates that they can have slightly higher values of emittance. The measured values for these coatings varied from 0.84 at 800° F to 0.94 at 1,800° F.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Air Force Base, Va., October 13, 1961.

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Figure 1.- General view of emittance measuring apparatus with identification of principal components.

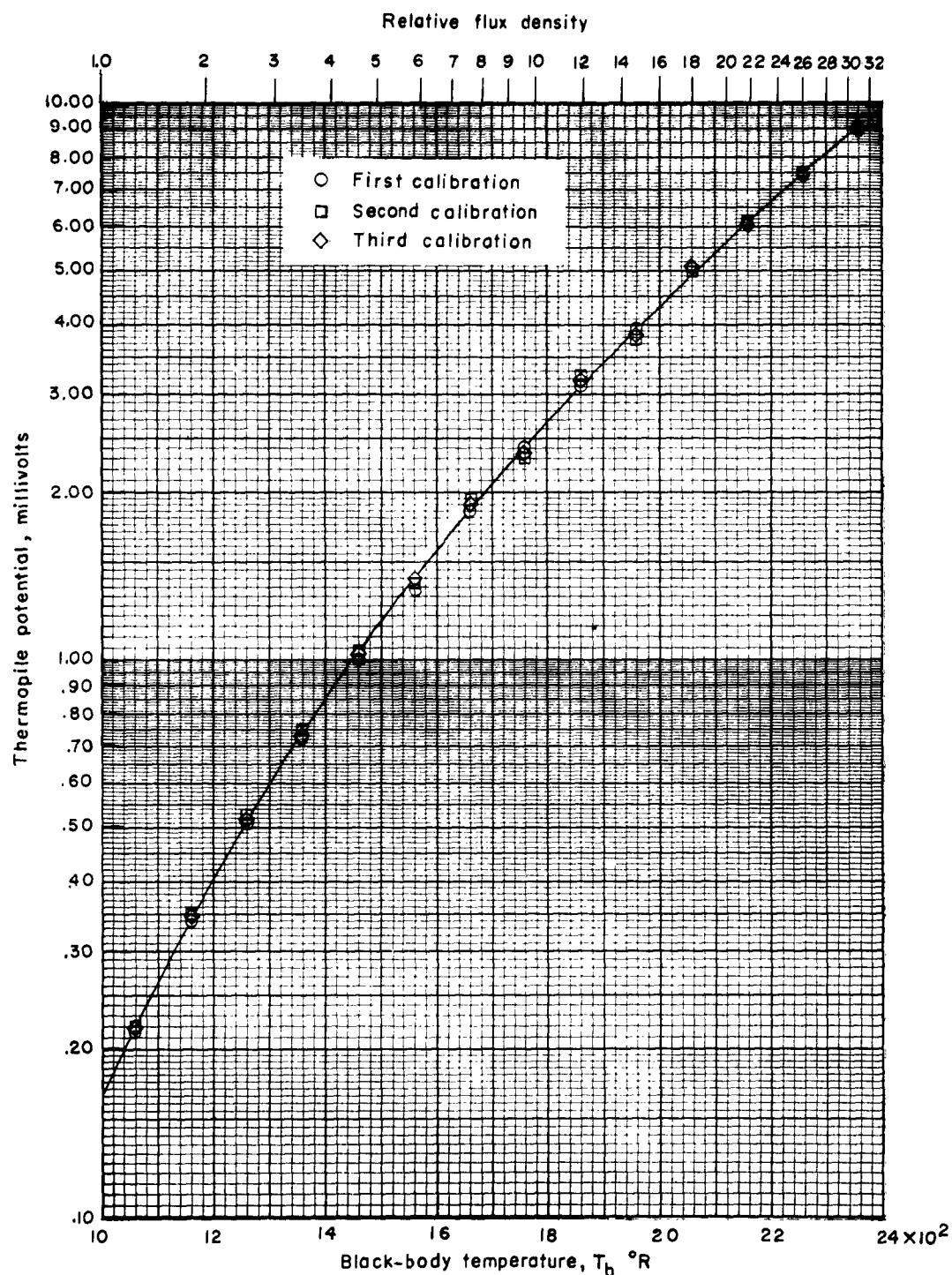


Figure 2.- Calibration of the thermopile radiant flux density measuring system.

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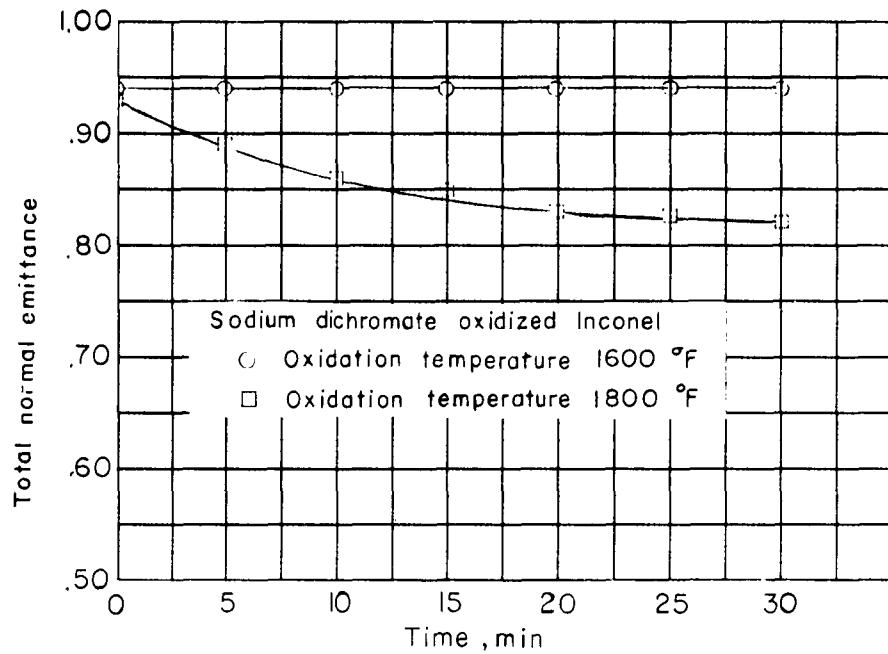


Figure 3.- Variation of the total normal emittance of chemically oxidized Inconel with time of heating in quiescent air.

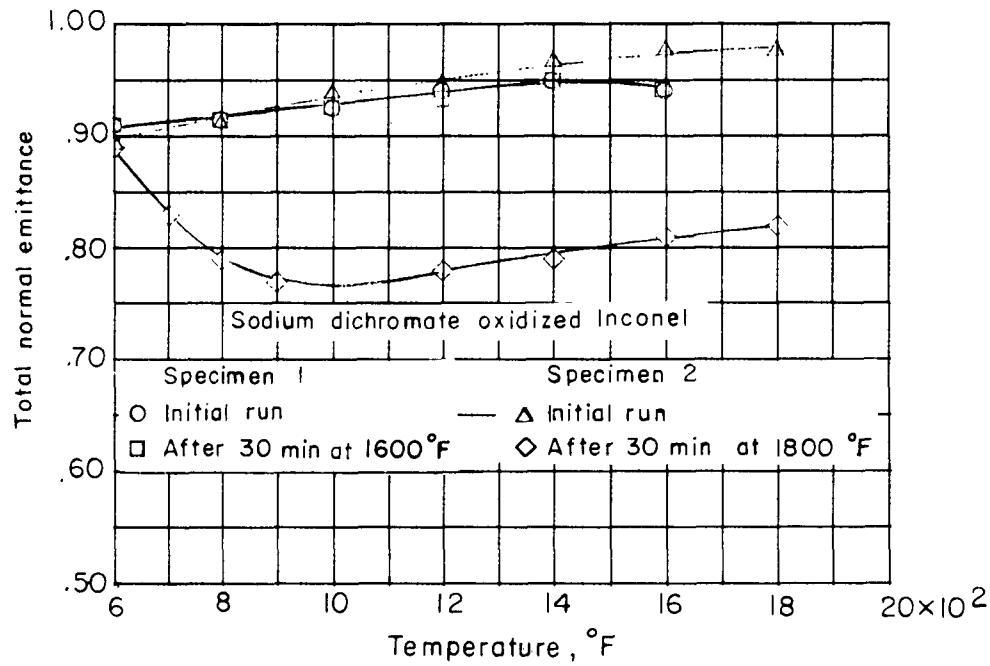


Figure 4.- Variation of the total normal emittance of chemically oxidized Inconel as a function of temperature.

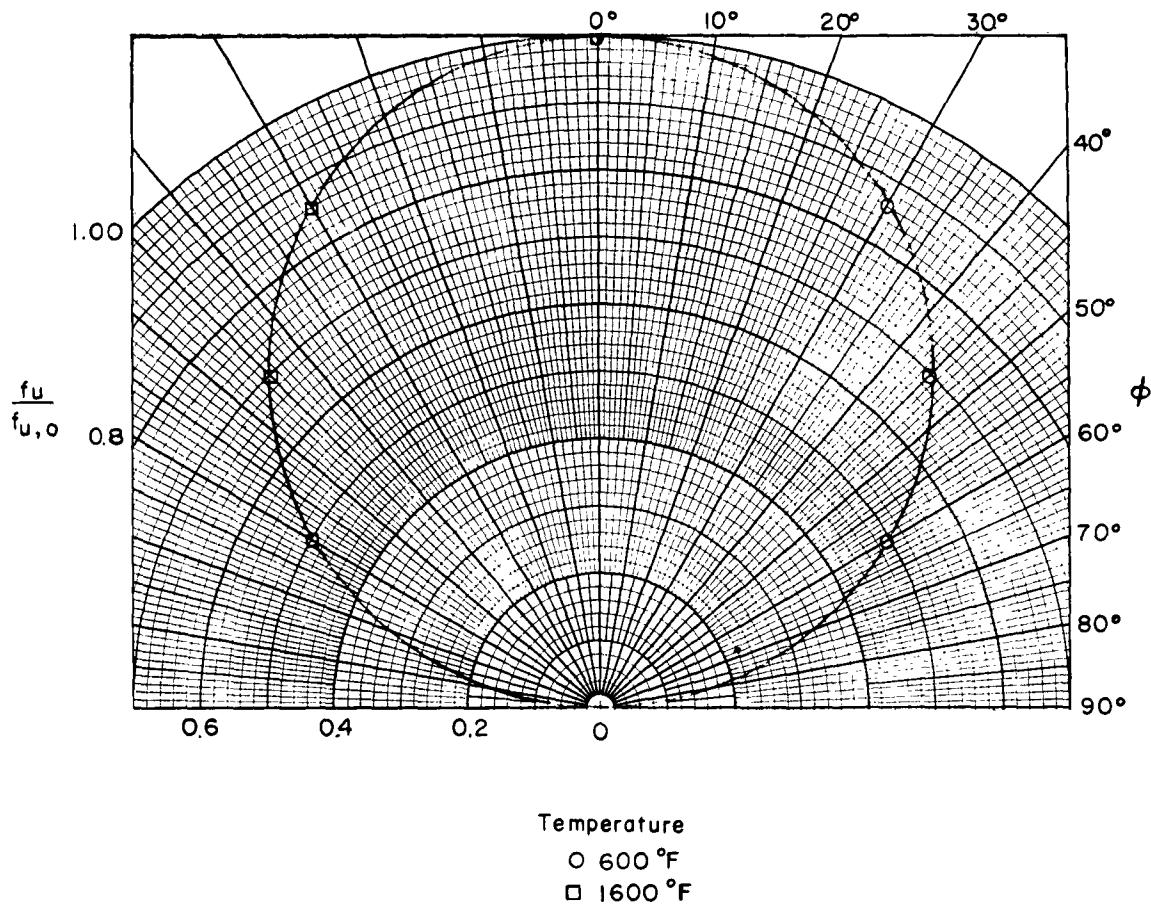


Figure 5.- Comparison of the radiant flux density of sodium dichromate oxidized Inconel heated for 30 minutes at 1,600° F with Lambert's cosine law for diffuse emission.

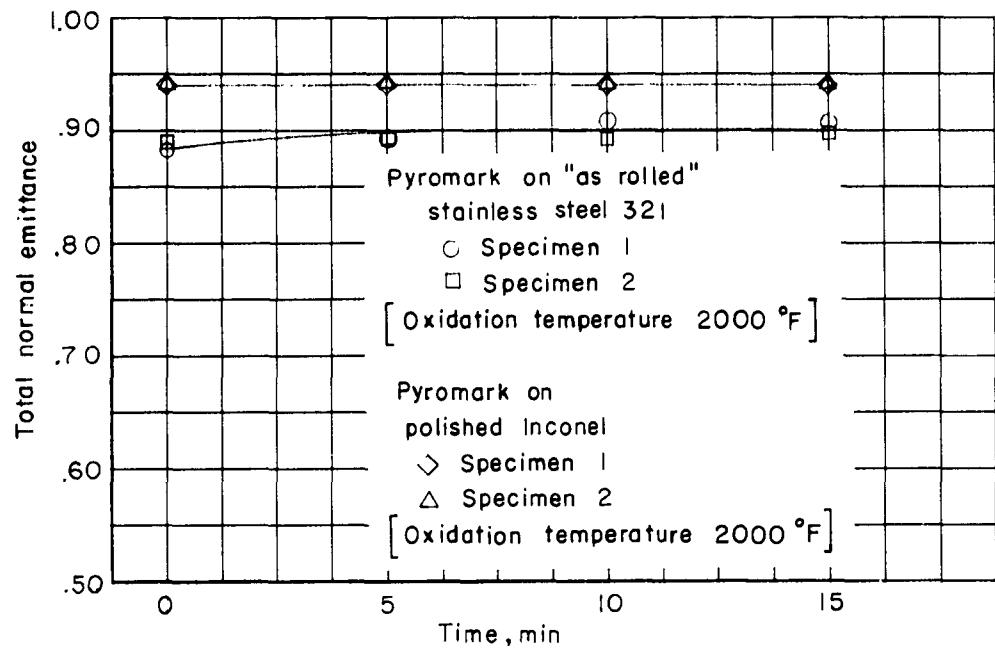


Figure 6.- Variation of the total normal emittance of Pyromark coating with time of heating in quiescent air.

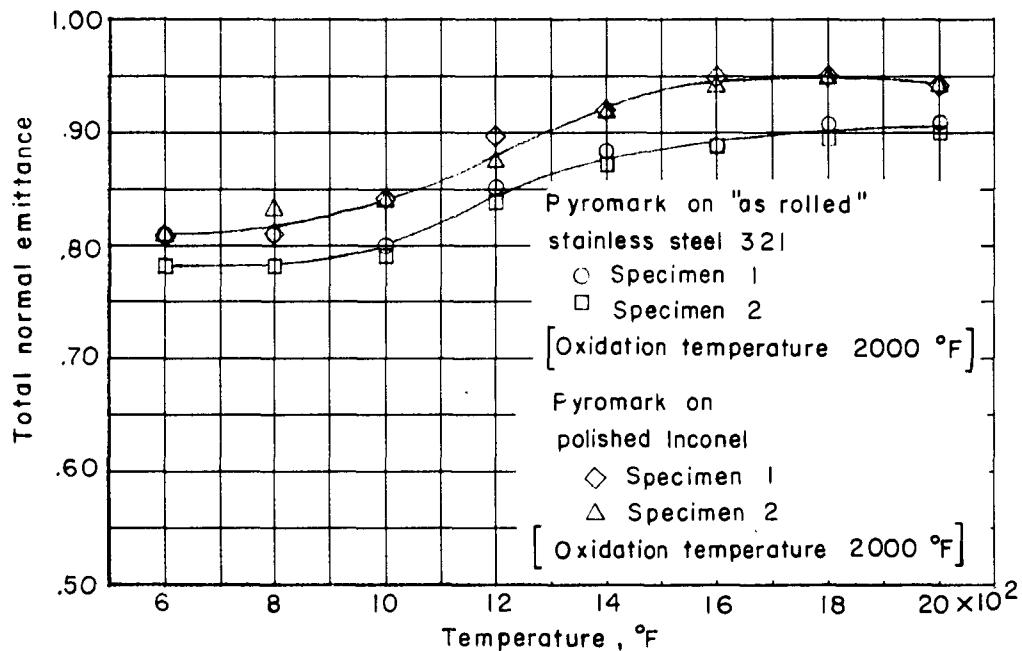


Figure 7.- Variation of the total normal emittance of Pyromark coating as a function of temperature.

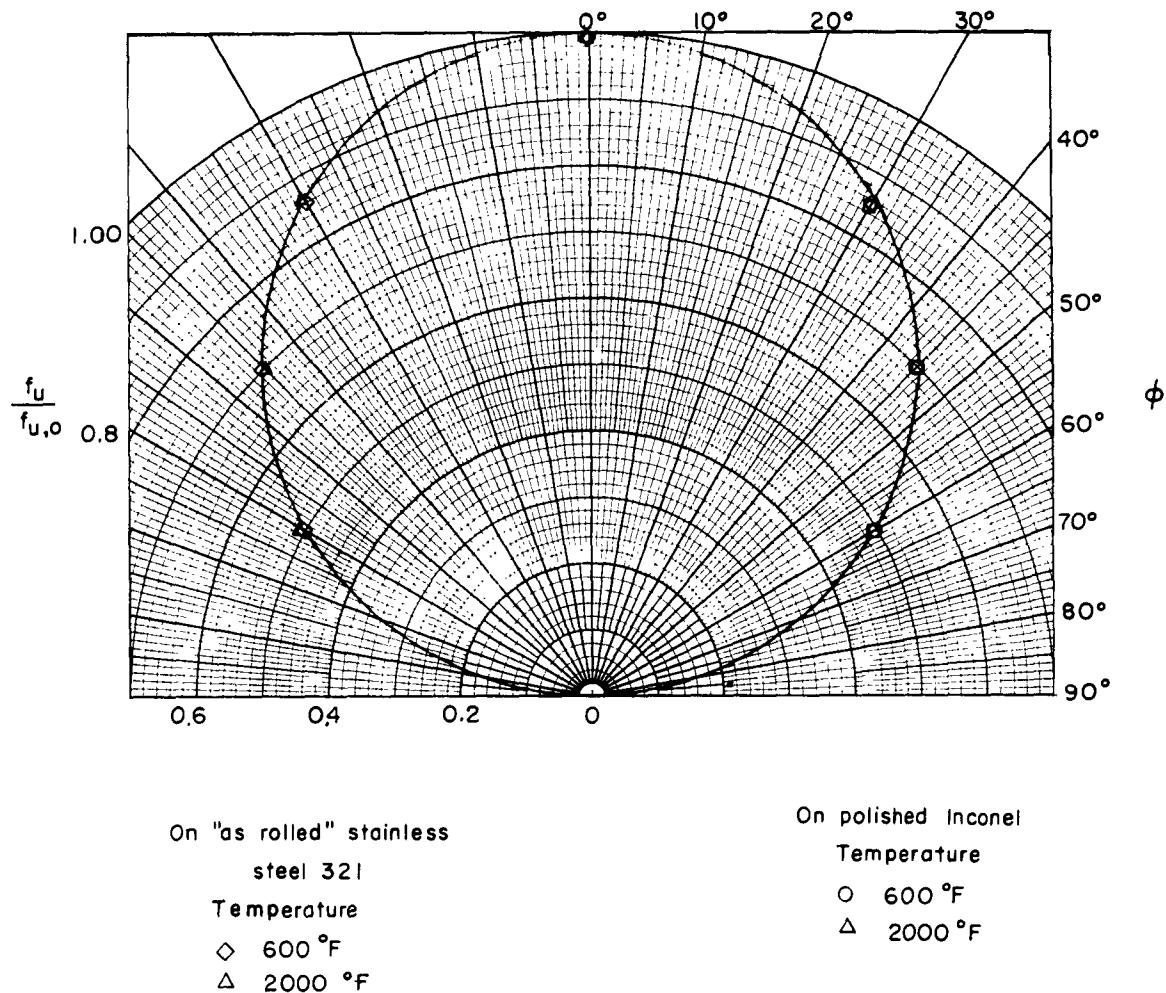


Figure 8.- Comparison of the radiant flux density of Pyromark coating on as-rolled stainless steel 321 and on polished Inconel heated for 15 minutes at 2,000° F with Lambert's cosine law for diffuse emission.

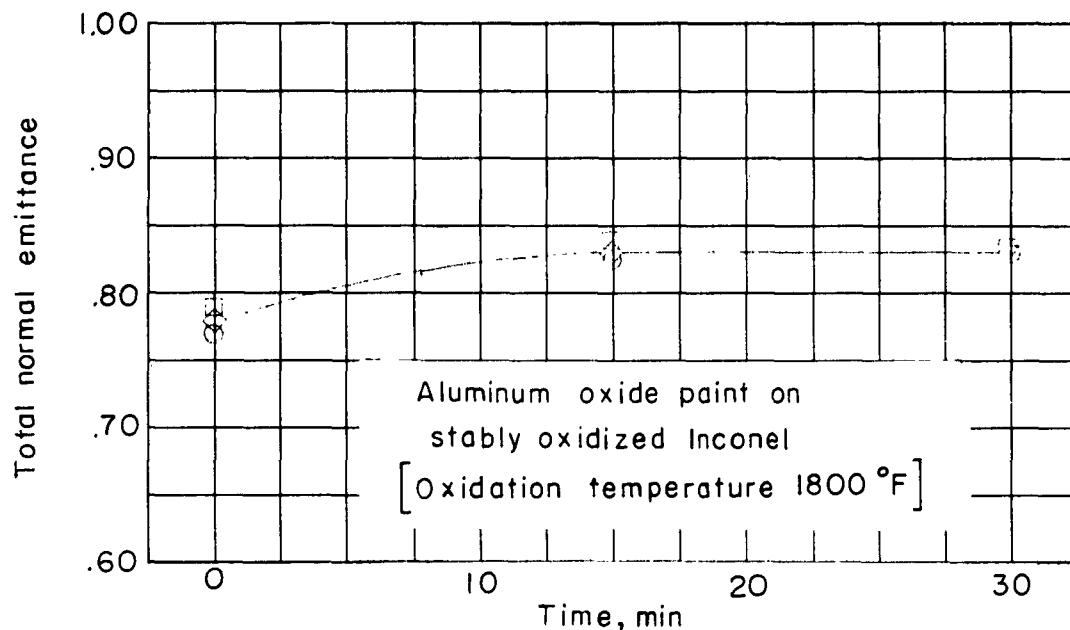


Figure 9.- Variation of the total normal emittance of aluminum oxide paint with time of heating in quiescent air.

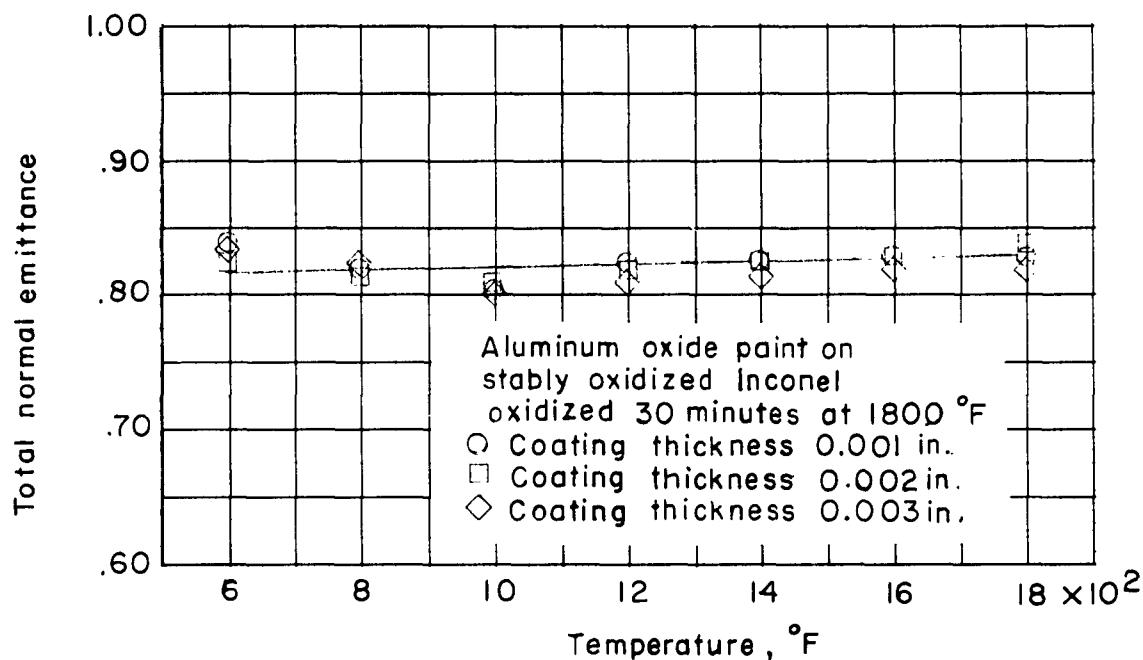


Figure 10.- Variation of the total normal emittance of aluminum oxide paint as a function of temperature.

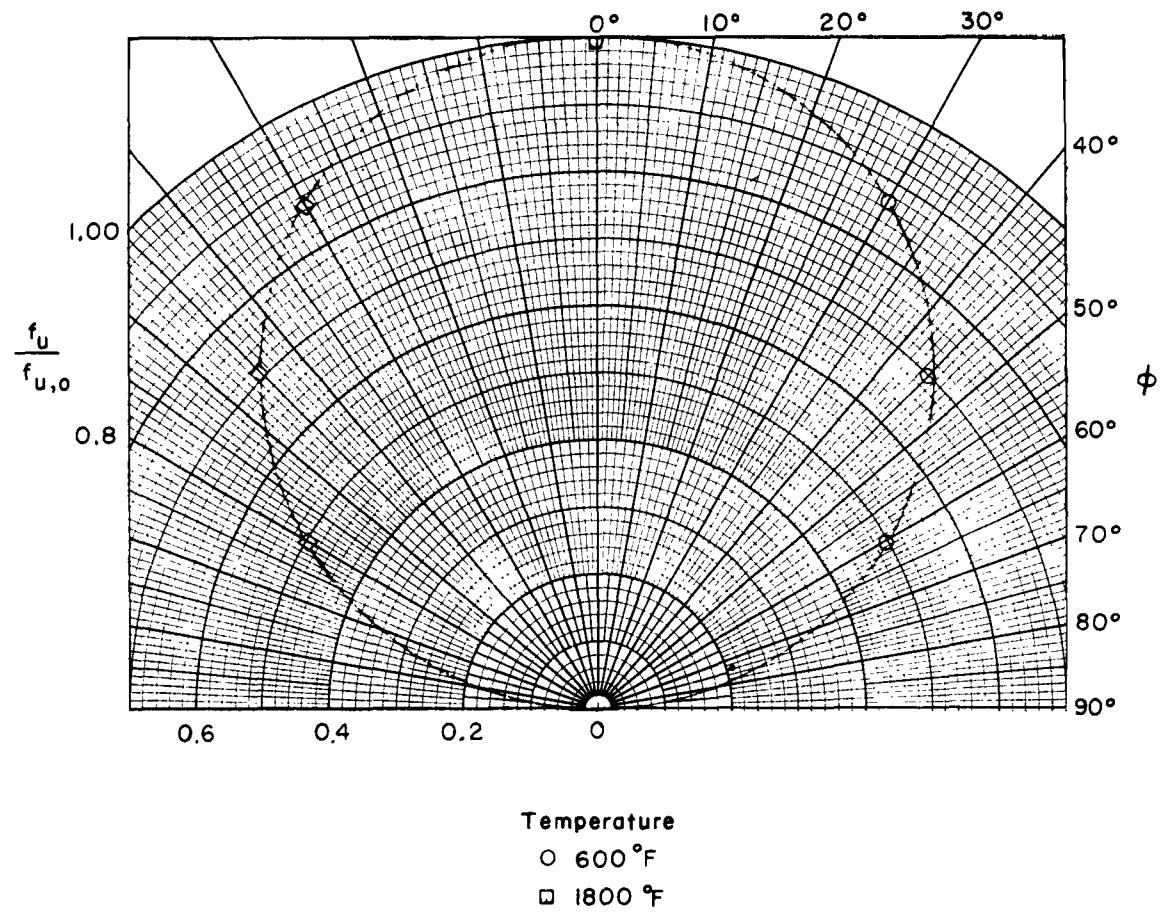


Figure 11.- Comparison of the radiant flux density of aluminum oxide paint on stably oxidized Inconel heated for 30 minutes at 1,800° F with Lambert's cosine law for diffuse emission.

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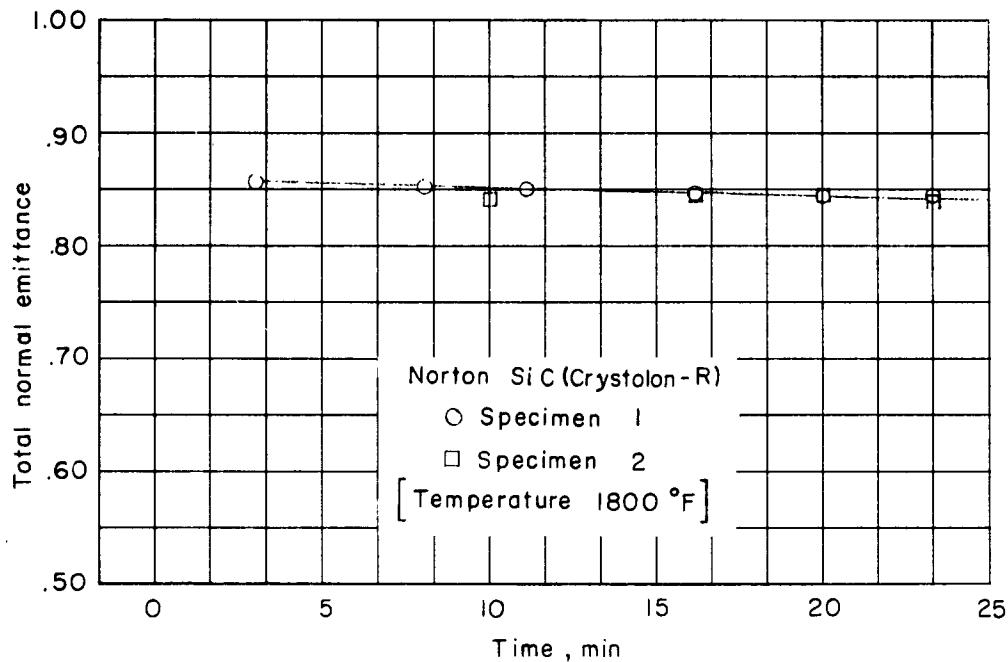


Figure 12.- Variation of the total normal emittance of silicon carbide with time of heating in quiescent air.

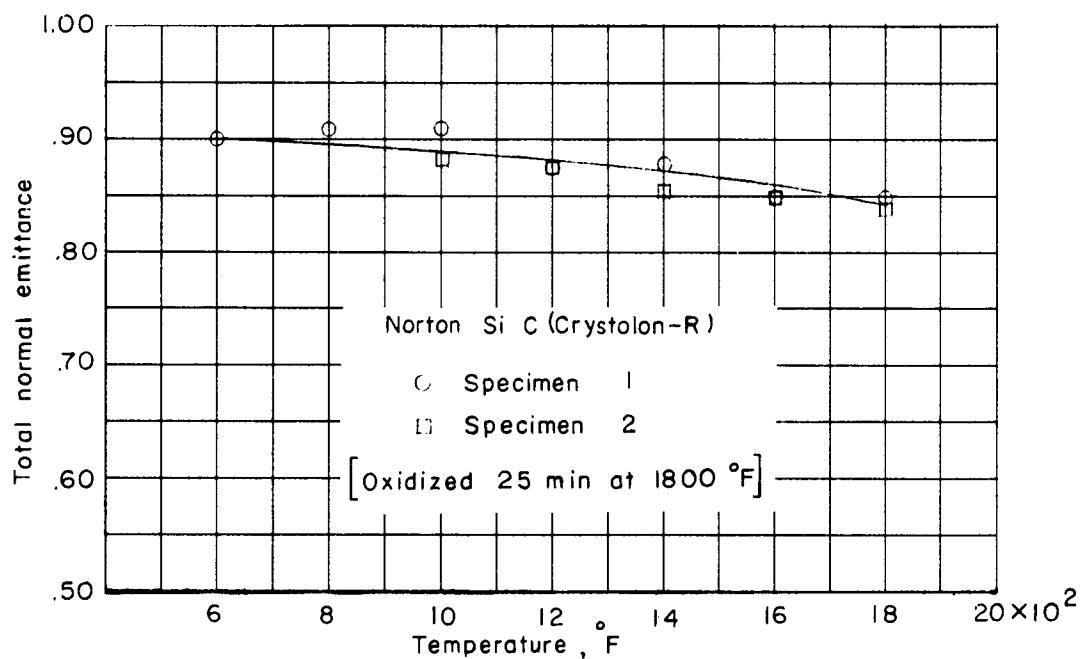


Figure 13.- Variation of the total normal emittance of stably oxidized silicon carbide as a function of temperature.

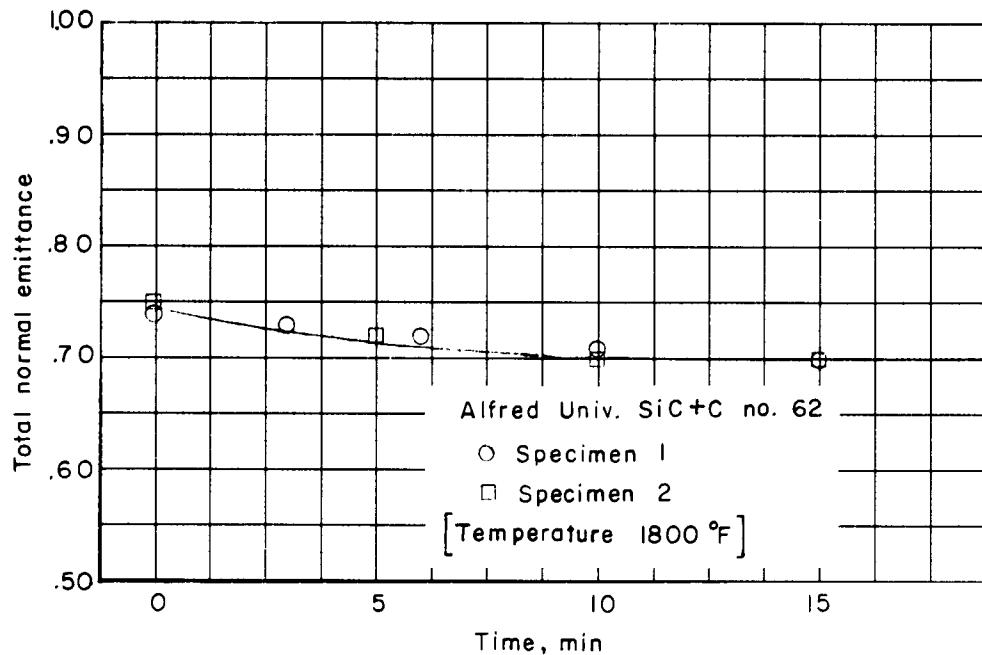


Figure 14.- Variation of the total normal emittance of a silicon carbide and carbon mixture with time of heating in quiescent air.

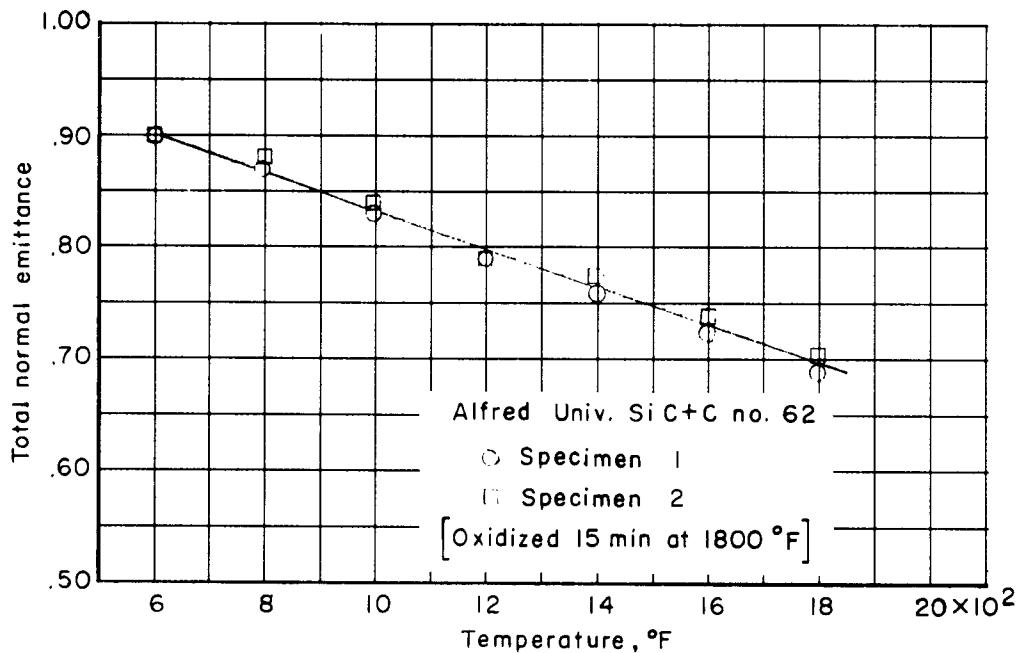


Figure 15.- Variation of the total normal emittance of a stably oxidized silicon carbide and carbon mixture as a function of temperature.

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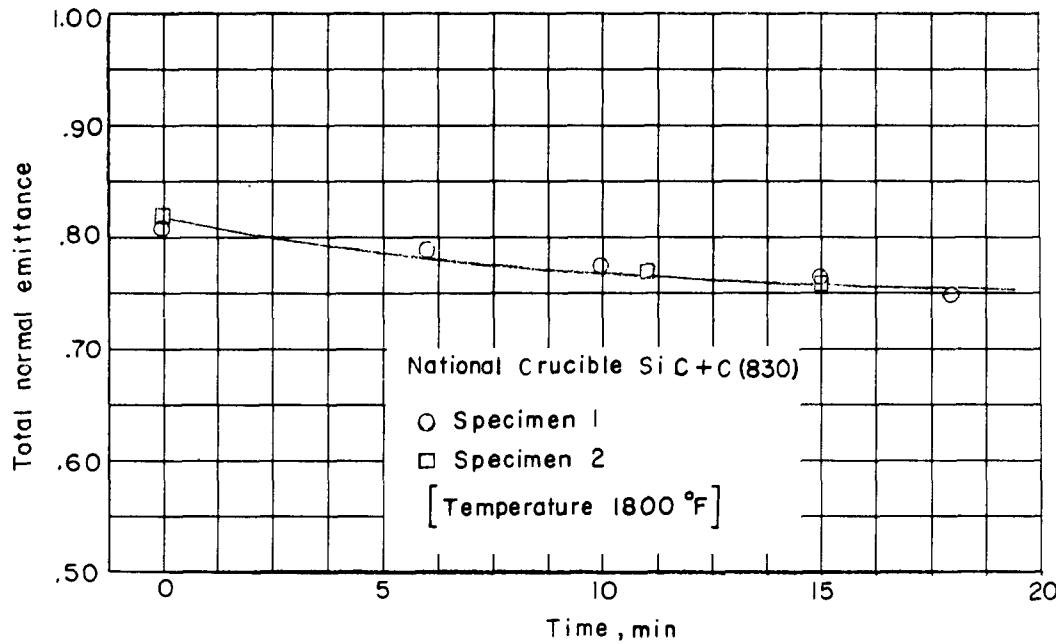


Figure 16.- Variation of the total normal emittance of a silicon carbide and carbon mixture with time of heating in quiescent air.

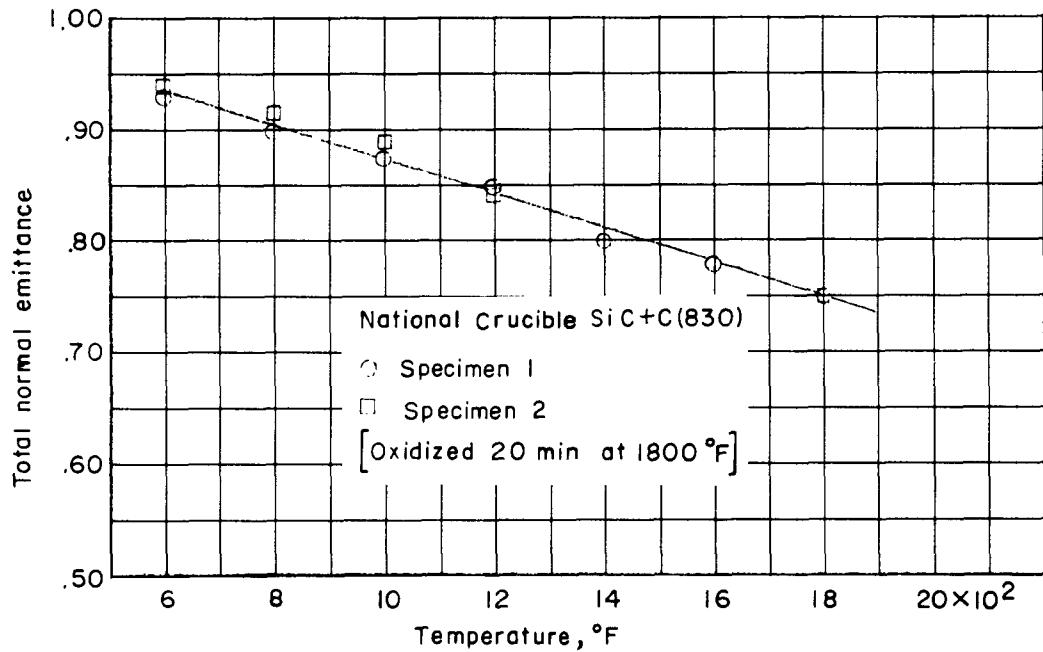


Figure 17.- Variation of the total normal emittance of a stably oxidized silicon carbide and carbon mixture as a function of temperature.

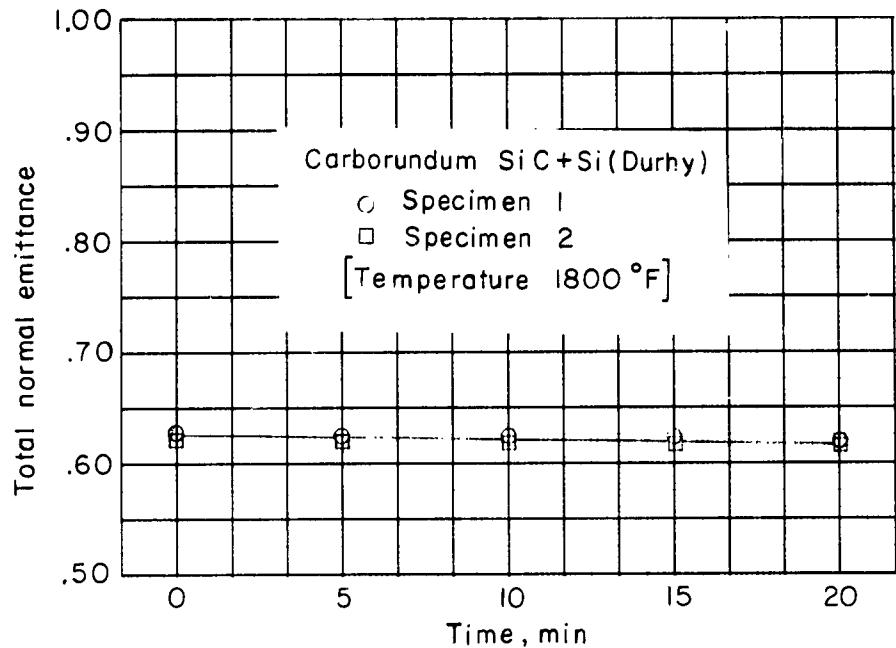


Figure 18.- Variation of the total normal emittance of a silicon carbide and silicon mixture with time of heating in quiescent air.

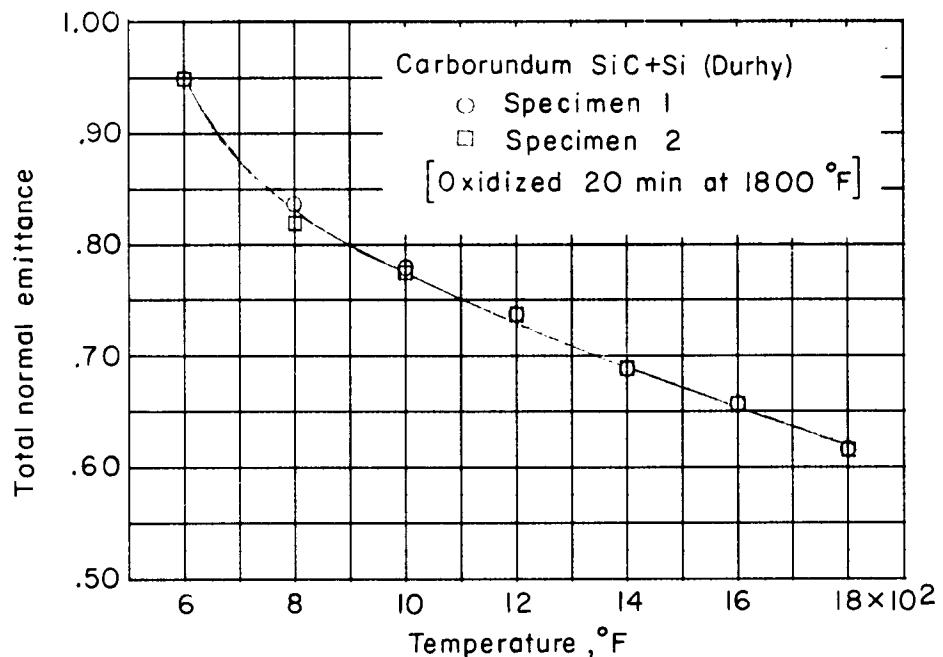


Figure 19.- Variation of the total normal emittance of a stably oxidized silicon carbide and silicon mixture as a function of temperature.

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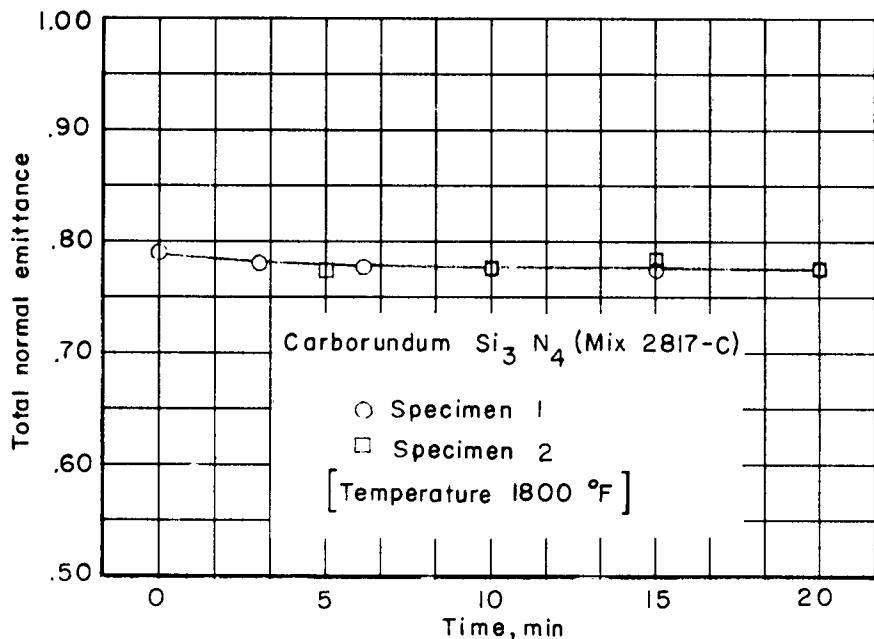


Figure 20.- Variation of the total normal emittance of a silicon nitride compound with time of heating in quiescent air.

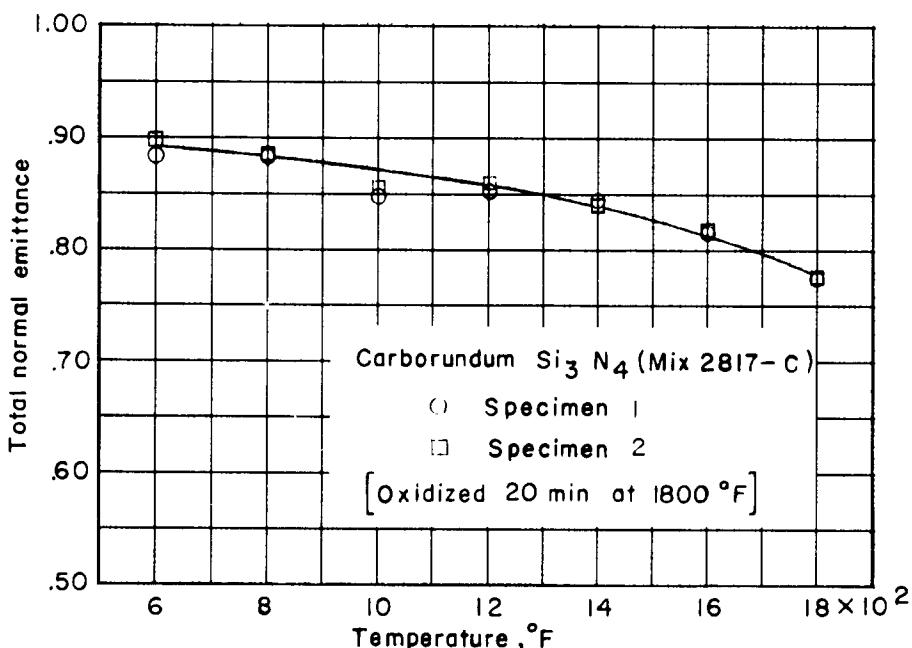


Figure 21.- Variation of the total normal emittance of stably oxidized silicon nitride as a function of temperature.

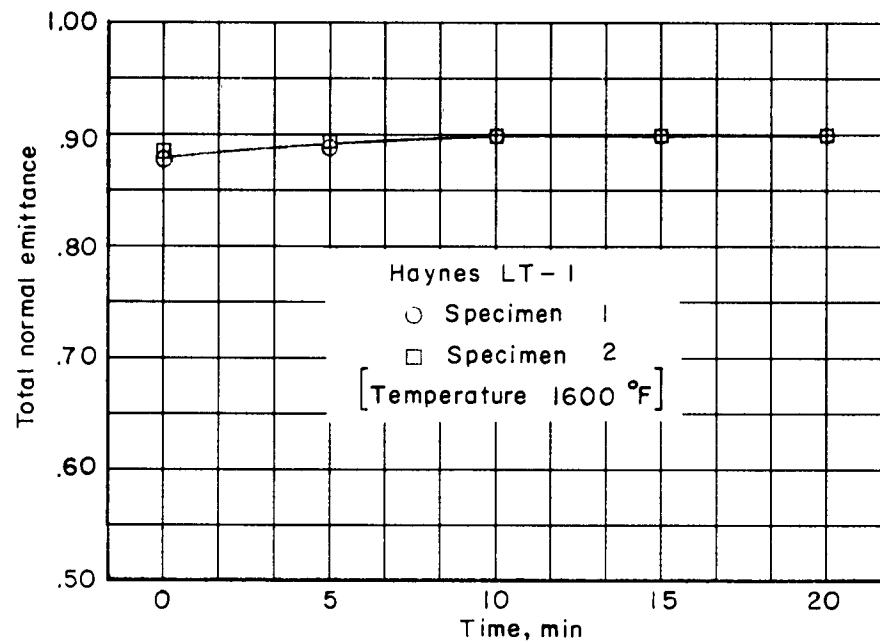


Figure 22.- Variation of the total normal emittance of Haynes LT-1 cermet with time of heating in quiescent air.

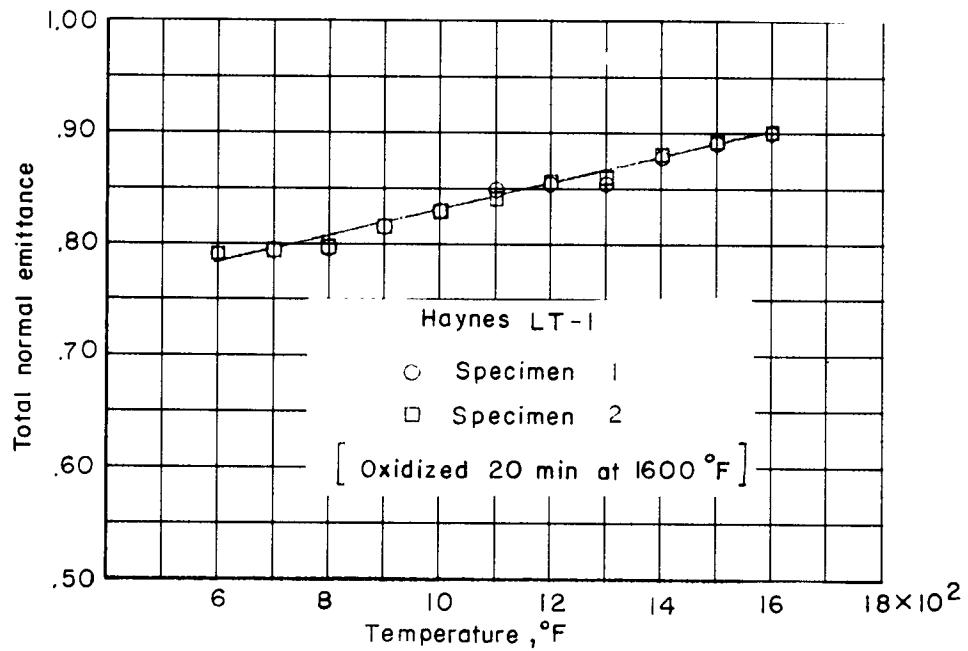


Figure 23.- Variation of the total normal emittance of stably oxidized Haynes LT-1 cermet as a function of temperature.

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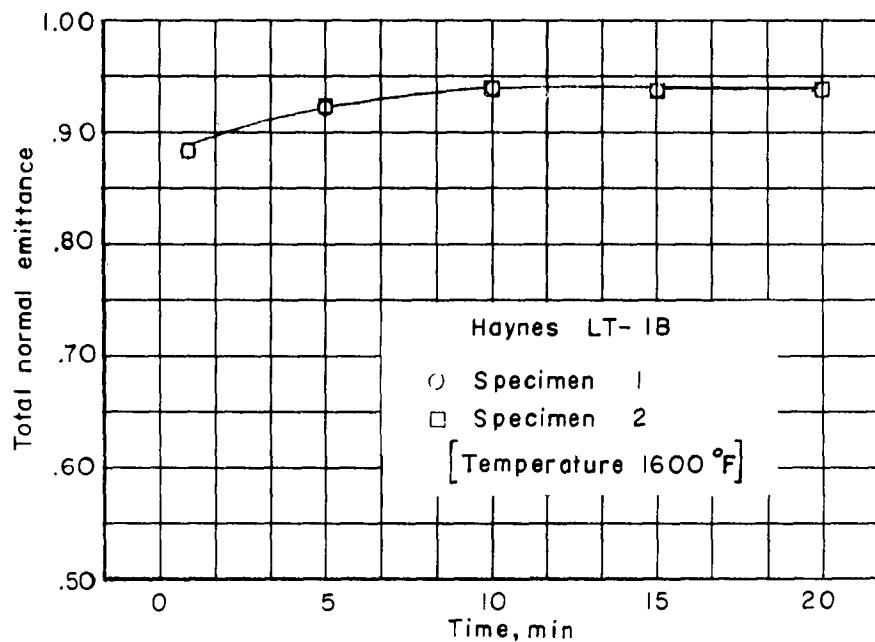


Figure 24.- Variation of the total normal emittance of Haynes LT-1B cermet with time of heating in quiescent air.

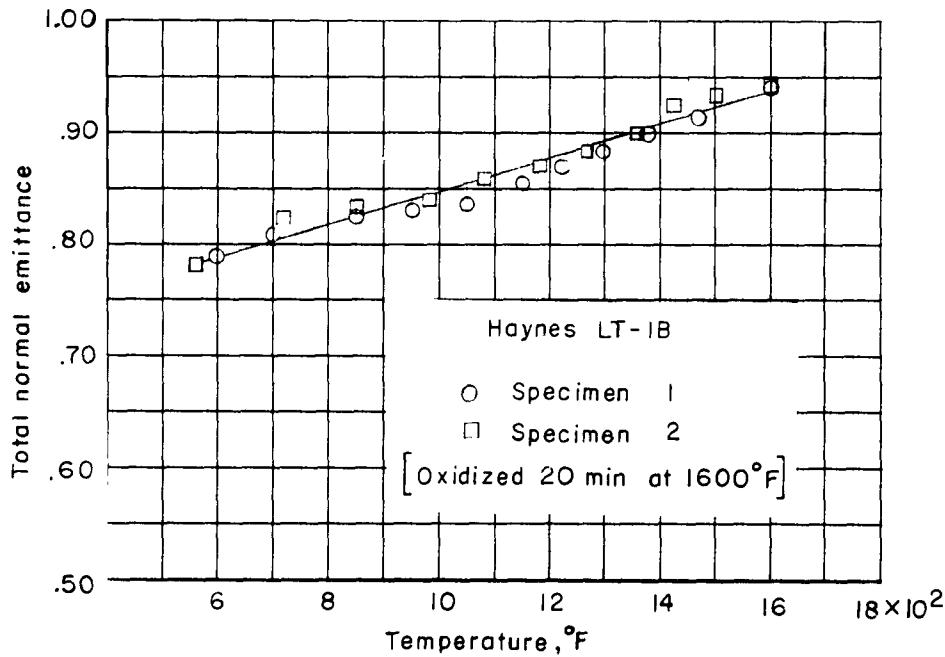


Figure 25.- Variation of the total normal emittance of stably oxidized Haynes LT-1B cermet as a function of temperature.

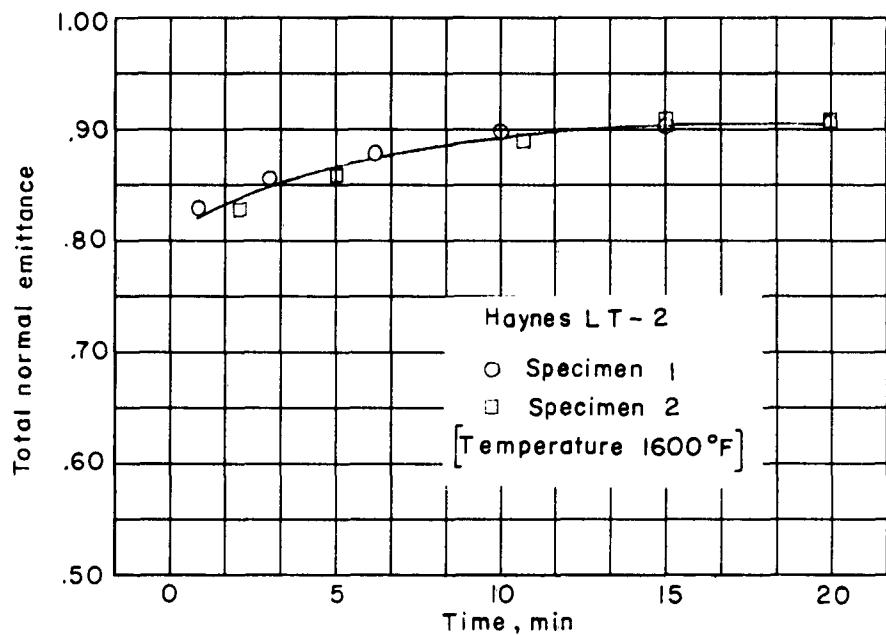


Figure 26.- Variation of the total normal emittance of Haynes LT-2 cermet with time of heating in quiescent air.

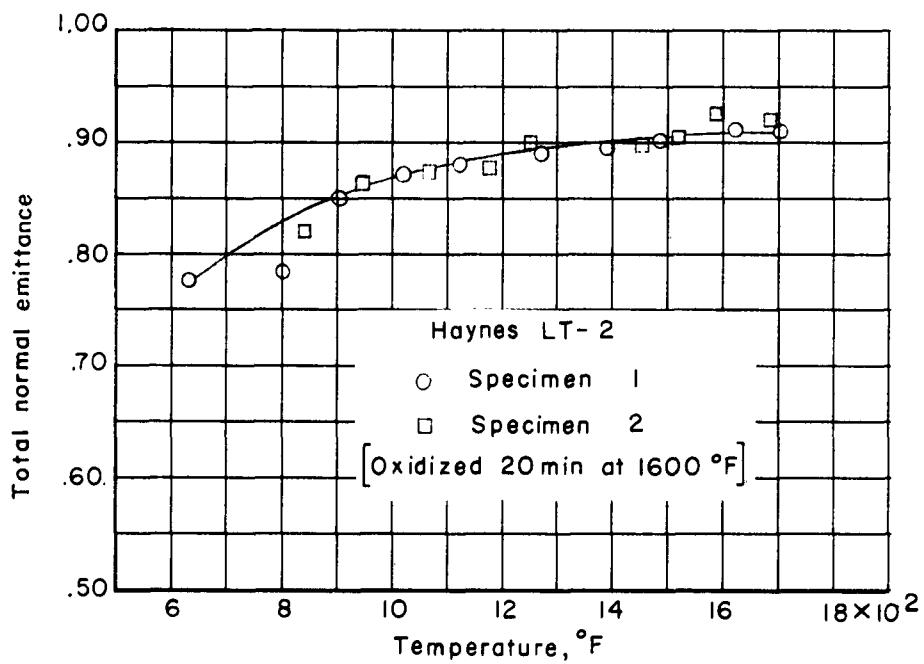


Figure 27.- Variation of the total normal emittance of stably oxidized Haynes LT-2 cermet as a function of temperature.

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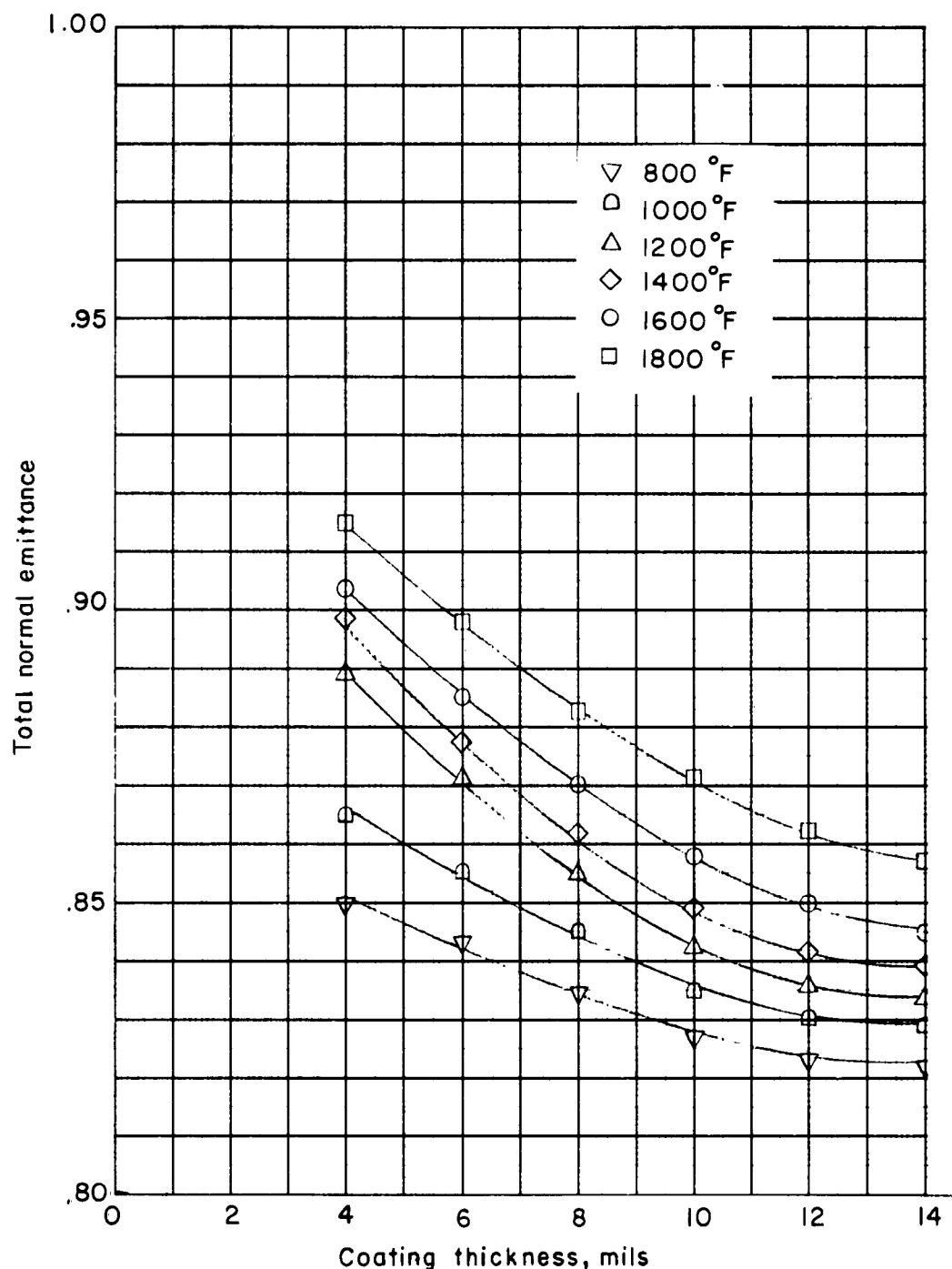


Figure 28.- Total normal emittance of flame-sprayed Haynes LT-1 cermet coating on sandblasted oxidized Inconel as a function of coating thickness.

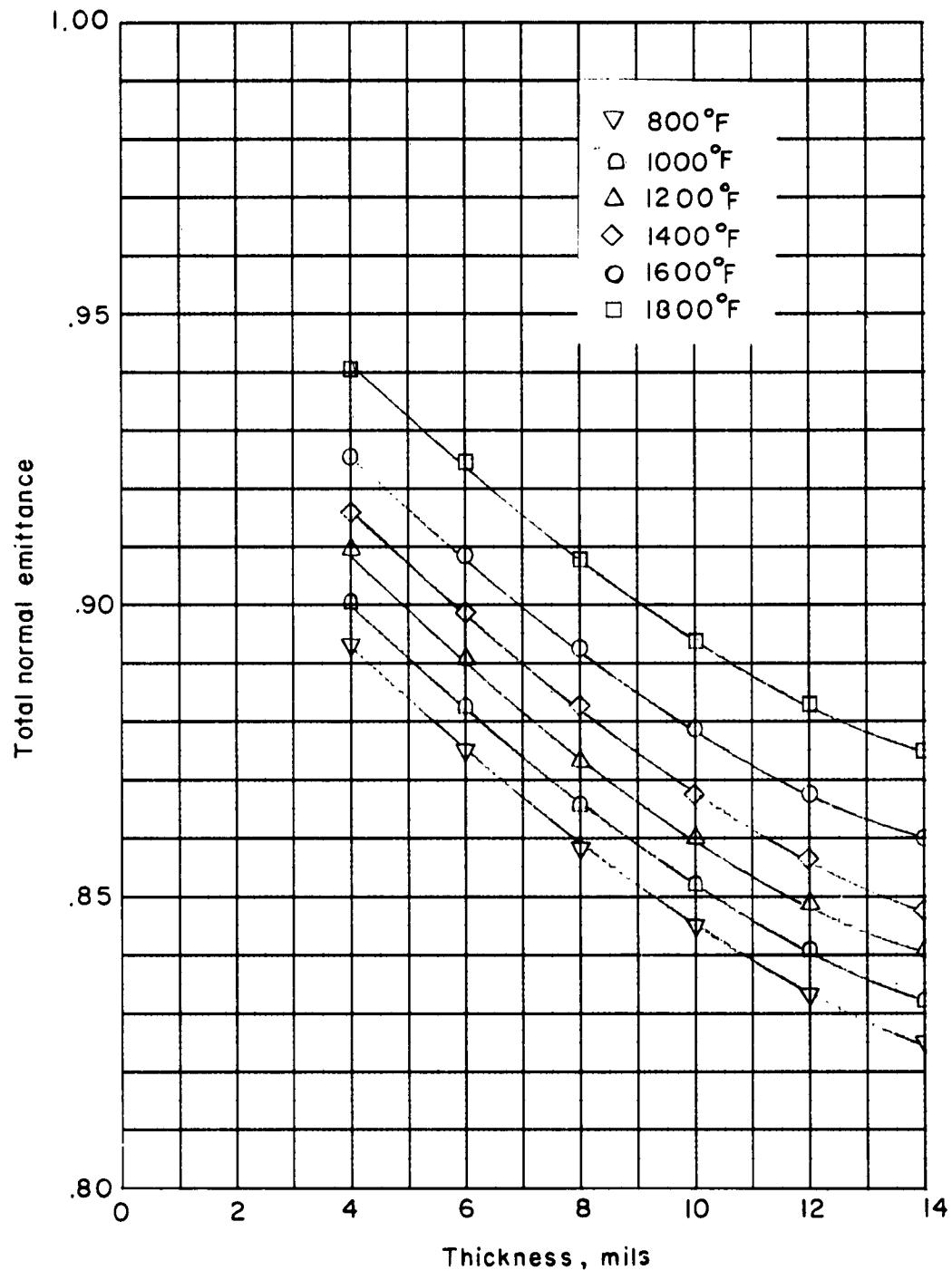


Figure 29.- Total normal emittance of flame-sprayed Haynes LT-1B cermet coating on sandblasted oxidized Inconel as a function of coating thickness.

L-1572

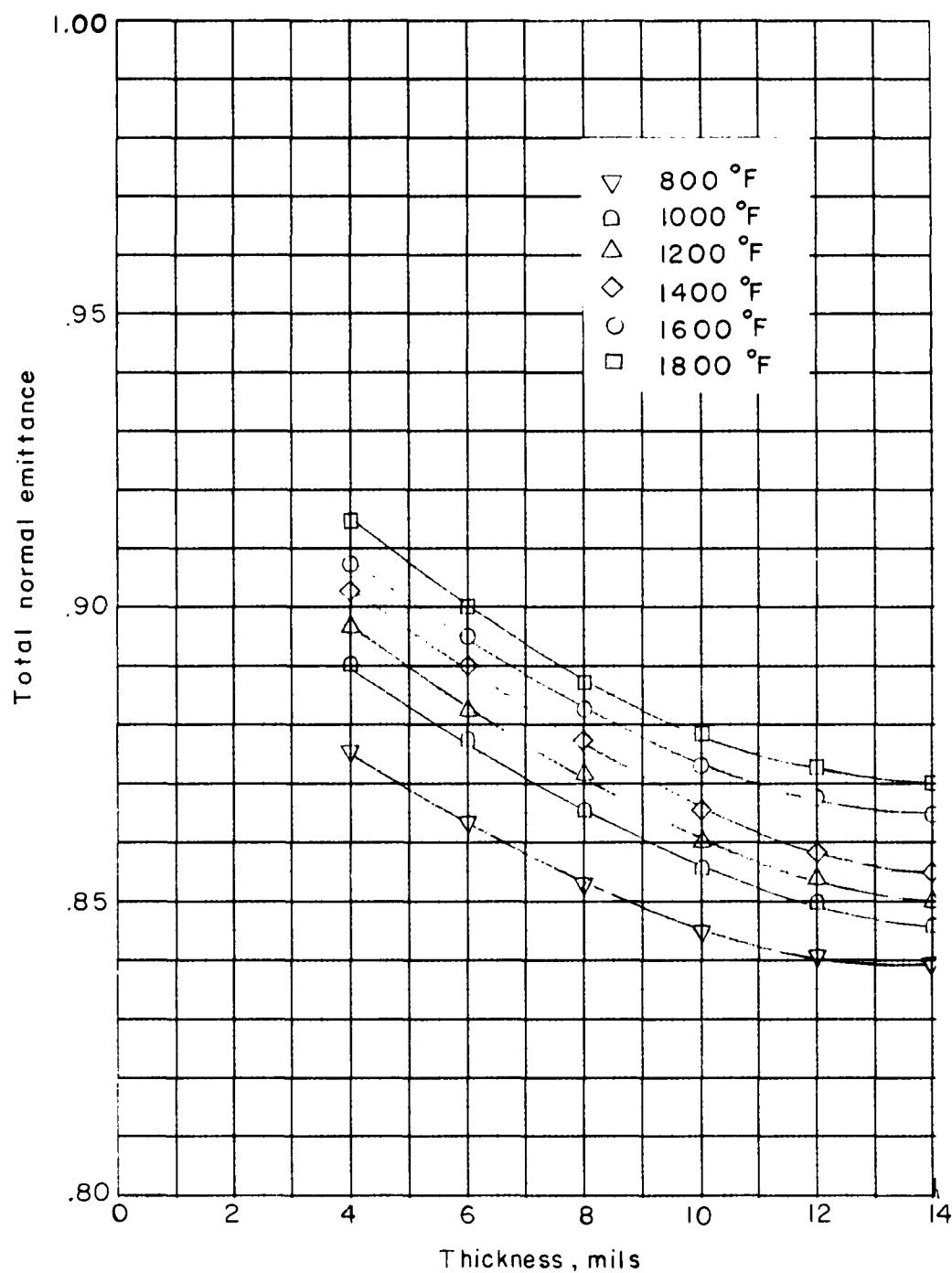


Figure 30.- Total normal emittance of flame-sprayed Haynes LT-2 cermet coating on sandblasted oxidized Inconel as a function of coating thickness.

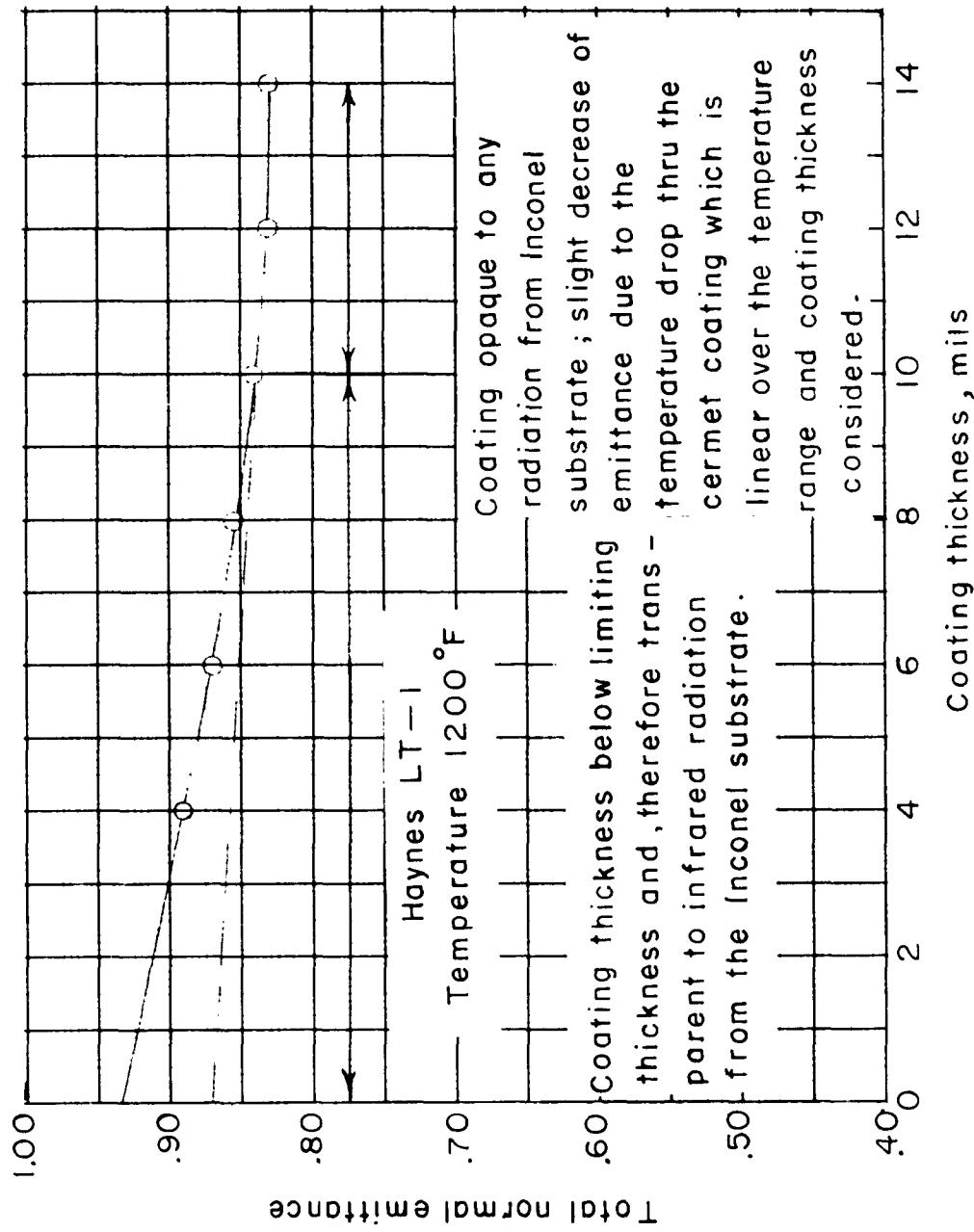
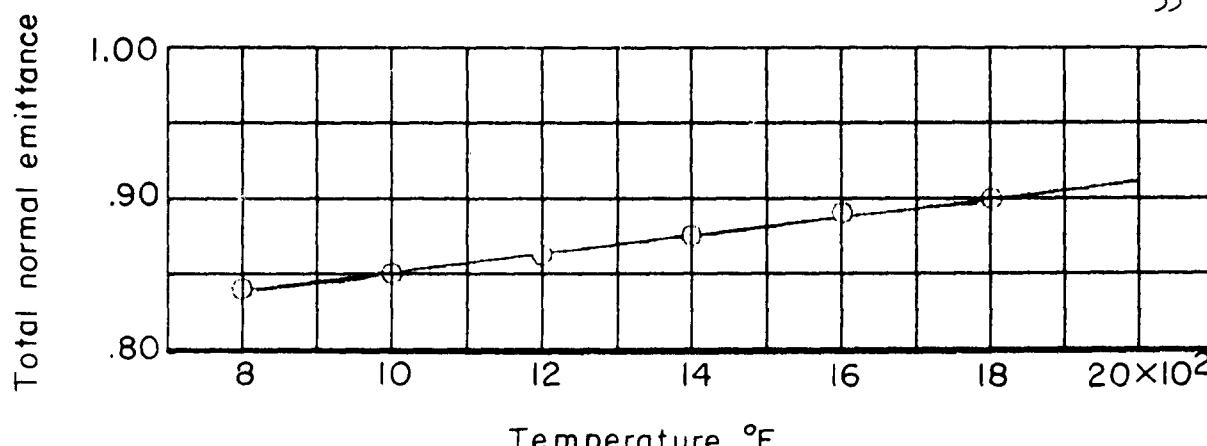
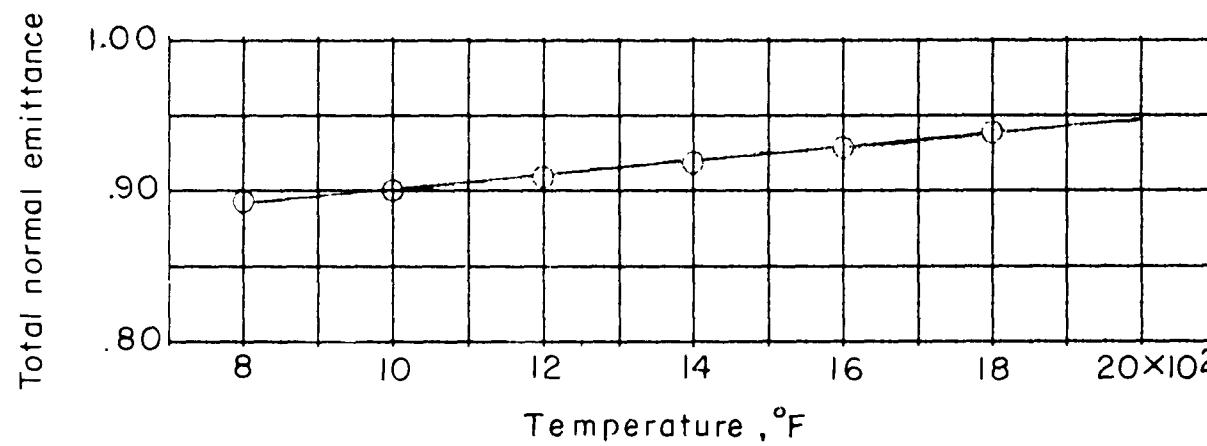


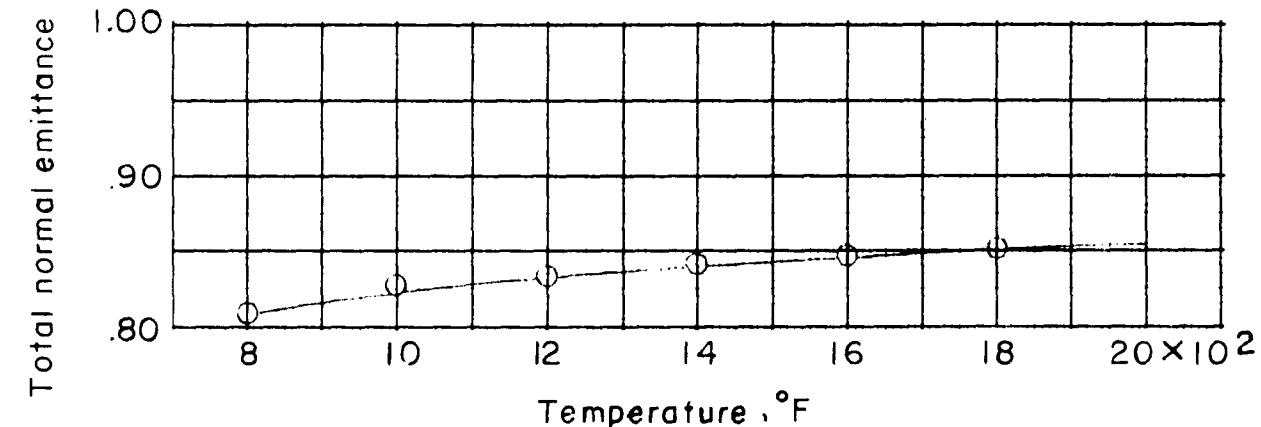
Figure 31.- Total normal emittance of flame-sprayed Haynes LT-1 cermet coating on sandblasted oxidized Inconel.



(a) Haynes LT-1.



(b) Haynes LT-1B.



(c) Haynes LT-2.

Figure 52-- Total normal emittance of flame-sprayed Haynes cermets on sandblasted oxidized Inconel as a function of the substrate temperature.

<p>NASA TN D-998 National Aeronautics and Space Administration. MEASUREMENTS OF TOTAL EMITTANCE OF SEVERAL REFRACTORY OXIDES, CERMETS, AND CERAMICS FOR TEMPERATURES FROM 6000 F TO 2,000^o F. William R. Wade and Wayne S. Slemp. March 1962. 35p. OTS price, \$1.00. (NASA TECHNICAL NOTE D-998)</p> <p>This paper is one of a series concerned with a program to determine values of total emittance of various materials which may possibly be used as construction materials for the radiative cooling of high supersonic and hypersonic aircraft. These materials include chemically oxidized Inconel, aluminum oxide and chromium oxide base paints, silicon carbide base ceramics, and chromium aluminum oxide cermets.</p>	<p>NASA TN D-998 National Aeronautics and Space Administration. MEASUREMENTS OF TOTAL EMITTANCE OF SEVERAL REFRACTORY OXIDES, CERMETS, AND CERAMICS FOR TEMPERATURES FROM 6000 F TO 2,000^o F. William R. Wade and Wayne S. Slemp. March 1962. 35p. OTS price, \$1.00. (NASA TECHNICAL NOTE D-998)</p> <p>This paper is one of a series concerned with a program to determine values of total emittance of various materials which may possibly be used as construction materials for the radiative cooling of high supersonic and hypersonic aircraft. These materials include chemically oxidized Inconel, aluminum oxide and chromium oxide base paints, silicon carbide base ceramics, and chromium aluminum oxide cermets.</p>	<p>NASA</p> <p>Copies obtainable from NASA, Washington</p>	<p>NASA</p> <p>Copies obtainable from NASA, Washington</p>
<p>I. Wade, William R. II. Slemp, Wayne S. III. NASA TN D-998</p> <p>(Initial NASA distribution: 25. Materials, engineering: 52. Structures.)</p> <p>I. Wade, William R. II. Slemp, Wayne S. III. NASA TN D-998</p> <p>(Initial NASA distribution: 25. Materials, engineering: 52. Structures.)</p> <p>I. Wade, William R. II. Slemp, Wayne S. III. NASA TN D-998</p> <p>(Initial NASA distribution: 25. Materials, engineering: 52. Structures.)</p> <p>I. Wade, William R. II. Slemp, Wayne S. III. NASA TN D-998</p> <p>(Initial NASA distribution: 25. Materials, engineering: 52. Structures.)</p>	<p>NASA TN D-998 National Aeronautics and Space Administration. MEASUREMENTS OF TOTAL EMITTANCE OF SEVERAL REFRACTORY OXIDES, CERMETS, AND CERAMICS FOR TEMPERATURES FROM 6000 F TO 2,000^o F. William R. Wade and Wayne S. Slemp. March 1962. 35p. OTS price, \$1.00. (NASA TECHNICAL NOTE D-998)</p> <p>This paper is one of a series concerned with a program to determine values of total emittance of various materials which may possibly be used as construction materials for the radiative cooling of high supersonic and hypersonic aircraft. These materials include chemically oxidized Inconel, aluminum oxide and chromium oxide base paints, silicon carbide base ceramics, and chromium aluminum oxide cermets.</p>	<p>NASA</p> <p>Copies obtainable from NASA, Washington</p>	<p>NASA</p> <p>Copies obtainable from NASA, Washington</p>
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